Preliminary Results from Feasibility Study for Motion Mitigation using M. Lis^{1,2}, W. Newhauser², M. Donetti³, C. Graeff¹ CNAO DDS at GSI

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Introduction

Tumors affected by respiratory motion continue to be a challenge to treat due to high amounts and large volumes of radiations necessary to achieve tumor control. Ion therapy decreases the dose deposition to surrounding tissue and can be exploited for moving tumors. A generally applicable strategy for delivering doses to moving tumors using the 4D robustly optimized approach could serve as a potential solution. This work aims to develop and validate a 4D optimized dose delivery system (DDS) which employs scanned ion beam irradiation on moving targets [1]. This system will ultimately be capable of delivering highly conformal irradiations to target volumes under realistic clinical situations.

System Design

The National Instruments (NI) based dose delivery system from CNAO (*Figure 1*) was updated and adapted at GSI to be compatible with the GSI hardware. The DDS was also modified to load entire treatment plan libraries, consisting of full treatment deliveries, divided across all of the motion phases according the predicted tumor movement behavior. The memory access was changed to block RAM for non-sequential dose deliveries. monitoring motion Α scan magnets detectors system (MMS), capable of multi-gating [2], which indicates motion the phase was developed to DDS scanning guide the motion table magnets during dose delivery. FPGAs

Experimental Setup

The treatment planning software, TRiP4D, utilizes 4D robust optimization to create treatment plans optimized for minimizing uncertainties in patient positioning, and for minimizing radiation to surrounding tissue. Simple 2D geometries were developed for validating the performance of the DDS, including vertical lines, 5 beam spots, square outlines and squares (Table 1) The geometries were delivered to a matrix detector and films mounted on a horizontally oscillating sliding platform, behind 10 cm of PMMA, as seen in the diagram below. Additionally, the gating functionalities and delivery speed were assessed and residual motion effected were measured by varying the motion amplitude and oscillation period.



Figure1. The DDS (1a) is based on NI FPGAs—*scan*FPGA, controlling the scanning magnets, *int*FPGA and *pos*FPGAs, managing integral and position detector readouts, and *tim*FPGA, sending timing events and communicating with the beam request. The experimental setup (1b) is a PTW Octavius detector mounted on a 1D oscillating platform.

Results

Both beam abort and the RF knockout gating tests were also performed and confirmed that multi-gating can be used for the DDS. Full beam recovery was achievable within 100 microseconds,

Geometry	Purpose	Analysis Method
Six vertical lines	Motion phase change accuracy	Data log review
Five spots	Spot shape and alignment	FWHM, gamma index
Outline squares	Interplay, residual motion, accuracy	Visual comparison, line width
5x10cm square 4, 5, 6, 7 m. phases	Homogeneity and uniformity	Dose intensity profile
6 vert line – 1, 3, 6, 10 m. phases	Effect of number of motion phases	Distance to agreement
Outline square 22mm and 42mm	Effect of amplitude of motion	Dose subtraction and line width
amplitude		
Six lines – irregular motion	Effect of irregular motion	Gamma index/distance to
		agreement

Table 1. Summary of geometries delivered for quantification of the impacts of motion under conditions including motion speed, duration of motion phase, motion amplitude, duration of individual spot delivery and irregular motion.

The delivered geometries were assessed for voxel-to-voxel distance to agreement. The pass rate threshold was set to 5mm, where x geometry produced highest pass rates, at x%. Residual motion increased the and beam deletion was almost instant, as seen in Figure 2. Residual FWHM from 5.5 mm, for static deliveries, to 14.7 mm for 3 phase deliveries, 6.0 mm for 6 phase deliveries, and 5.6 mm for 10 phase deliveries.

particle intensity after knockout will be analyzed and handled in

subsequent tests. Currently, the detuning of the cavity happens with a delay of 100 µs and a ramp of 1 ms, which was not fast enough to suppress the beam in the gate completely. Simple geometries with and without motion compensation



Figure 2. Knockout extraction and beam recovery time measurements on oscilloscope.

were delivered to detectors moving at 22 and 42 mm amplitudes remaining residual for both 6 and 10 motion phases, as summarized in *Table 1*. motion artifacts. Interplay patterns were observed in the absence of motion

For 50x100mm rectangle geometries, homogeneity increased from 51.9% for 1 motion phase deliveries, to 90.3% for 7 motion phase deliveries.

Significant interplay effects were visible for 1 motion phase deliveries, which mitigated were largely with more motion phases. Additional modifications can eliminate the





compensation, which were completely mitigated for 22mm, 10 motion phase plans, as seen in Figure 3. Residual motion was observed for 42mm motion plans. These doses were reconstructed in TRiP4D and compared.

Conclusions and Outlook

A 4D DDS is being developed and validated at GSI to achieve scanned carbon ion beam therapy for moving tumors. Simple geometries for one energy have been delivered with motion mitigation and gating functionalities. The results of the validation indicate that this system can deliver motion compensated treatments. Further validation of multi-energies and clinical feasibility tests are still in progress.

Figure 3. Square outline plans were delivered to the PTW Octavius 1500 detector with 22mm motion and (a) no motion compensation. The interplay effects can be seen in this plan. The same plan was repeated with (b) 3 motion phases to compensate for detector motion, with (c) 6 motion phases and with (d) 10 motion phases. Decreased residual motion within a motion phase was observed with more motion phases.

References

[1] Graeff, C., et al. (2013). "A 4D-optimization concept for scanned ion beam therapy." Radiother Oncol 109(3): 419-424. [2]Graeff, C., et al. (2014). "Multigating, a 4D optimized beam tracking in scanned ion beam therapy." <u>Technol Cancer Res</u> <u>Treat</u> **13**(6): 497-504.

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