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SHORTER TREATMENT TIME BY INTENSITY MODULATION WITH A BETATRON CORE EXTRACTION

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Abstract

The CNAO (National Center for Oncological Hadrontherapy) main accelerator is a synchrotron capable to accelerate carbon ions up to 400 MeV/u and protons up to 250 MeV. Three treatment rooms are available and are equipped with horizontal beam lines; one of the treatment rooms also features a vertical treatment line to allow additional treatment ports. All of the beamlines are equipped with an active beam scanning system for dose delivery. With such a dose distribution technique, particles are sent to different depths by changing the energy from the synchrotron and are moved transversally by means of two scanning magnets. The number of particles to be deposited in each position varies strongly within the same iso-energetic layer. Part of the dose needed in a given position is in fact delivered by particles directed to deeper layers. In order to maintain the required precision on the number of particles delivered to each spot, the intensity is reduced when spots that require low number of particles are present in a layer. A method to shorten the irradiation time based on variable intensity within the same layer is presented that works also with a betatron based extraction scheme.

INTRODUCTION

CNAO (Centro Nazionale di Adroterapia Oncologica), the Italian synchrotron-based medical accelerator center for oncological hadrontherapy [1], started clinical operation in September 2011 and by the end of December 2017 more than 1600 tumor patients were treated using the spot scanning method.

With this dose delivery system, the tumor is irradiated slice-by-slice, each slice corresponding to a different beam energy, starting from the proximal slice. Within a single slice, the beam is scanned from one voxel to the other by means of a couple of scanning magnets. The beam distribution at CNAO is "dose driven", that is the beam is kept on the spot until the monitors in front of the patient *measure* that the prescribed number of particles has been delivered. The beam is not switched off during the displacement to the following position, unless the distance between the two points is larger than 20 mm.

To determine the number of particles to be delivered to a given spot, the contribution of the dose deposited by spots directed to more distal slices has to be taken into account. This generally implies highly inhomogeneous dose distributions within one iso-energetic slice. Typically the maximum over minimum fluence ratio in a slice is in the order of 100, but it can be in excess of 1000. As an example, Figure 1 shows the number of particles required in the spots of a slice

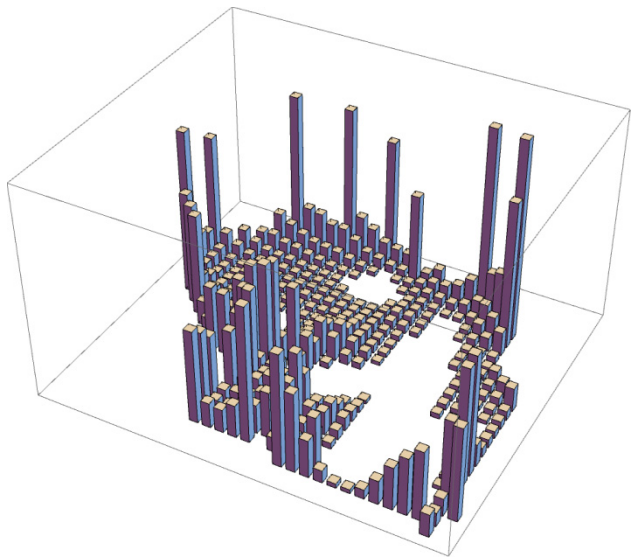

Figure 1: The number of particles required in different positions within the same iso-energy slice varies by more than two orders of magnitude.

The voxel requiring the lowest dose in a given slice determines the intensity of the beam spill delivered to that slice. Therefore, a large variation in particle fluence, within a single slice, can have a non-negligible impact on the irradiation time.

BETATRON CORE DRIVEN SLOW EXTRACTION AT CNAO

For clinical treatments, beam extraction from the synchrotron needs to be a slow, controlled process, lasting several seconds, in order to guarantee an adequate measurement and control of the delivered radiation doses.

The betatron core-driven 3rd order resonance extraction method has been implemented at CNAO and is used to extract particles from the synchrotron in a nominal spill length between 1 and 10 seconds.

At the end of the acceleration process in the synchrotron, the beam horizontal tune is moved close to the resonance Q_x = 5/3. Short before extraction, a sextupole in a nondispersive synchrotron region is switched on to excite the resonance. Then, the betatron core slowly accelerates the beam into the resonance activating the extraction process, by effectively moving the horizontal tune towards the 3rd order integer resonance [2], as illustrated in Figure 2.

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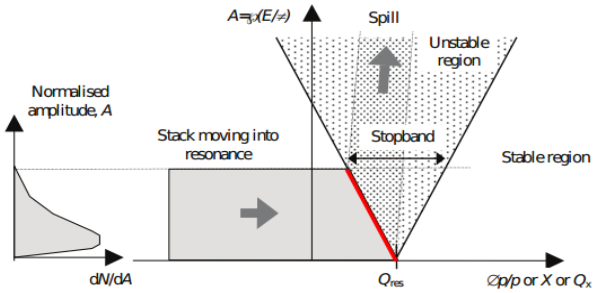

Figure 2: Betatron core driven extraction mechanism.

Adjusting the betatron induced voltage, it is possible to vary the intensity of the extracted beam. Four levels of intensity are presently foreseen at CNAO [3], defined slice by slice. An intra-spill intensity modulation is not presently used at CNAO.

BEAM PARAMETERS

The irradiation time of a patient treatment depends on beam intensity: ideally, the higher the intensity, the faster the treatment. Besides the performance of the accelerator, other technical issues limit, in practice, the maximum usable beam intensity.

In order to define the intensity required for a given slice a few parameters are considered.

The *permanence time* of the beam on a single spot should be large enough to limit position errors, due to the movement duration with respect to the voxel irradiation time, and to allow a precise measurement by means of the strip chambers located just upstream the isocenter. At CNAO, a single raster point must be irradiated for at least 300 μs.

The *minimum number of particles* deliverable in a single spot is one of the parameters defined in the Treatment Planning System (TPS), and is presently set to $5.5{\cdot}10^5$ for protons and to $1{\cdot}10^4$ for carbon ions.

The *standard intensity* of protons and carbon ions, is defined considering both the accelerator performance and some medical physicist's considerations; The standard intensities presently used are $2.5{\cdot}10^9$ s^{-1} for protons and $6{\cdot}10^7$ s^{-1} for carbon ions.

The *spill ripple,* that is intensity fluctuations along the spill, is defined in this paper as the 99.5th percentile of the intensity over the average intensity, measured with an integration time of the ionization chamber signal of 100 μs (10 kHz). The spill ripple, depending mainly on the ripple of the synchrotron power supplies, depends on particle and energy. Taking a single value for each particle, the values used for the spill ripple are 3 for protons and 4.5 for carbon ions.

Taking into account all these parameters, each slice in a treatment is analyzed and a *degrader* value is chosen for the whole slice. The possible degrader values are presently 100%, 50%, 20% and 10% of the standard beam intensity and are obtained by adapting the betatron core induced voltage.

INTENSITY MODULATION

The idea of adapting the beam intensity to the voxel is not novel [4], [5]. It was proposed for machines based on the RF-KO extraction, which have a fast response between the RF exciter and the intensity variation.

In the betatron core driven extraction the response time is longer due to the low amplitude particles participating to the spill and, at CNAO, because of the empty bucket channeling and empty bucket sweeping HFRI. Moreover the betatron core itself, with its power supply, is a slow object.

A spot by spot intensity modulation is not feasible in the same way it was proposed for RF-KO.

It is important to notice that delays in intensity variation are not equally important when the intensity is increasing and when intensity is decreasing. In the first case the slow current variation only leads to a longer treatment time while a too slow beam current reduction could lead to a hot spot, as illustrated in Figure 3

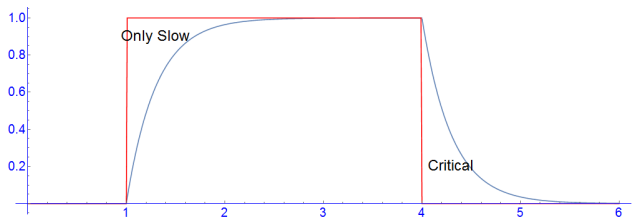

Figure 3: A slow response to intensity variation only leads to longer treatment time when increasing and might lead to a hot spot when decreasing.

The proposed method foresees the reorganization of the voxel sequence of each slice. The voxels shall be grouped in five classes, corresponding to five different beam intensities. For each of the voxels the maximum beam intensity, also taking into account the assumed ripple, must be low enough that in the minimum permanence time the dose is not exceeded. The five classes correspond to five equivalent degrader values, that is 10%, 20%, 50%, 100% and 200% of the standard intensity. The 200% class may be surprising but the presently used standard intensity is still below the nominal CNAO intensity and there is therefore margin for increasing the current in voxels that require large enough dose.

Table 1 summarizes the number of particles needed for a voxel to belong to a given intensity class.

Table 1: Minimum and Maximum Number of Particles for the Different Intensity Classes for Protons and Carbon Ions. The Deg10 Class is Not Used for Protons

	PROTONS		CARBON IONS	
Deg	**N_{min}**	**N_{max}**	**N_{min}**	**N_{max}**
10	$2.25{\cdot}10^5$	$4.50{\cdot}10^5$	$8.10{\cdot}10^3$	$1.62{\cdot}10^4$
20	$4.50{\cdot}10^5$	$1.13{\cdot}10^5$	$1.62{\cdot}10^4$	$4.05{\cdot}10^4$
50	$1.13{\cdot}10^5$	$2.25{\cdot}10^6$	$4.05{\cdot}10^4$	$8.10{\cdot}10^4$
100	$2.25{\cdot}10^6$	$4.50{\cdot}10^6$	$8.10{\cdot}10^4$	$1.62{\cdot}10^5$
200	$4.50{\cdot}10^6$		$1.62{\cdot}10^5$	

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The subdivision of a slice in sub-slices, illustrated in Figure 4, allows starting with the lowest required intensity for the slice and eventually increasing the intensity during the spill. In this way the intensity variation is always made in the safe direction.

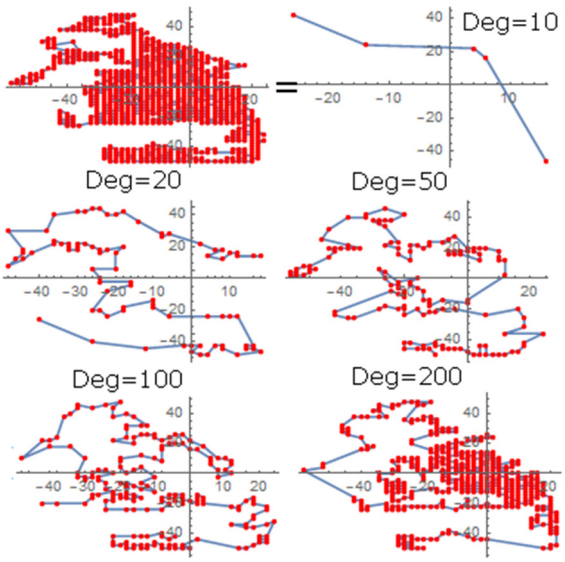

Figure 4: Example of voxels re-arrangement in growing intensity classes for a tumor slice irradiated with carbon ions in a real treatment plan.

The subdivision also requires re-sorting of the spot positions. This leads to a larger number of steps larger than 20 mm which, as anticipated, requires interrupting the spill. This is obtained with a fast magnetic system in the extraction line, called "chopper". The chopper power supply was designed for intervening (stopping and starting the beam again) continuously 10 times a second. Thus when re-sorting the spots, this shall be considered and might imply that the method is not applicable for the considered treatment plan.

SIMULATION RESULTS

The time to deliver the dose to the whole tumor target shall consider the pure beam time, the time requested by the betatron to adjust the tension from one intensity to the other, the intervention time of the chopper, the inter-spill time needed to accelerate a new beam to a larger energy or to the same energy when the particles in a single spill are not enough to irradiate a whole slice. The values used in this paper are shown in Table 2.

Table 2: Machine Time Parameters

Inter spill [s]	2.5
Betatron reaction time [ms]	25
Chopper intervention time [μs]	200

To estimate the efficacy of the intra-slice intensity modulation in reducing the irradiation time, almost 1000 treatment plans have been analyzed.

The time to irradiate the tumor target with intra-spill intensity modulation was compared with the one needed to irradiate each slice with the intensity determined by the voxel requiring the lowest number of particles in that slice. Absolute and relative time gains are shown in Figure 5 where the plans are sorted by increasing number of particles.

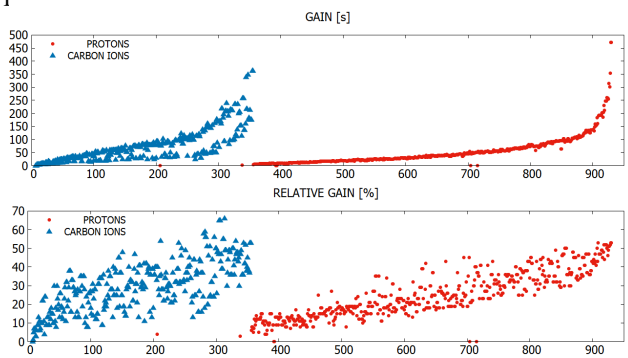

Figure 5: Absolute (upper panel) and relative (lower panel) time gain using intensity modulation. The plans are sorted by total number of particles.

Due to restricted computational resources, the simulations were limited to small and medium treatment plans. Although they represent the majority of clinical cases, the largest benefit of intensity modulation is obtained on larger plans. Taking the average of the cases analyzed, the irradiation time is reduced by 25% for protons and by 28% for carbon ions, with a maximum saving of 66% for carbon and of the 53% for protons.

Finally Figure 6 shows the number of chopper interventions for the same cases. The limit in the lower panel shall be set around 20, when the inter spill time is considered. Thus in most of the analyzed cases, intensity modulation is applicable from this point of view.

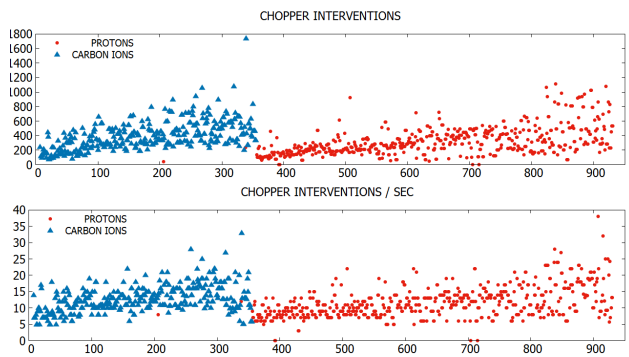

Figure 6: total number of chopper interventions per treatment plan and maximum number of chopper intervention *per second in a single slice* with intensity modulation.

CONCLUSIONS

Subdivision of slices in groups of voxels with similar fluence allows intensity modulation in a safe way also for a betatron driven slow extraction. The relative gain expected is in the order of 25% of the treatment time but for some particular treatment plans the implementation could be prevented by the large number of chopper interventions. In these cases the number of intensity classes could be reduced as a compromise solution.

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