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Monte Carlo simulations of ripple filters designed for proton and carbon ion beams in hadrontherapy with active scanning technique

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Abstract. Proton and carbon ion beams have a very sharp Bragg peak. For proton beams of energies smaller than 100 MeV, fitting with a gaussian the region of the maximum of the Bragg peak, the sigma along the beam direction is smaller than 1 mm, while for carbon ion beams, the sigma derived with the same technique is smaller than 1 mm for energies up to 360 MeV. In order to use low energy proton and carbon ion beams in hadrontherapy and to achieve an acceptable homogeneity of the spread out Bragg peak (SOBP) either the peak positions along the beam have to be quite close to each other or the longitudinal peak shape needs to be broaden at least few millimeters by means of a properly designed ripple filter. With a synchrotron accelerator in conjunction with active scanning techniques the use of a ripple filter is necessary to reduce the numbers of energy switches necessary to obtain a smooth SOBP, leading also to shorter overall irradiation times.

We studied the impact of the design of the ripple filter on the dose uniformity in the SOBP region by means of Monte Carlo simulations, implemented using the package Geant4. We simulated the beam delivery line supporting both proton and carbon ion beams using different energies of the beams. We compared the effect of different kind of ripple filters and their advantages.

1. Introduction

In the field of hadrontherapy two kinds of charged beams are used: proton and carbon ion beams. Two main irradiation techniques are also used: passive and active. The passive technique is widely used both with carbon ion beams (Japan) and with proton beams (Loma Linda).

The passive technique requires a significant effort in the definition of the modulating devices along the beam delivery line to reach a 3D-conformal dose distribution. The active scanning technique is more sophisticated: in the most straightforward application the beam is sequentially steered to each voxel of the target volume with millimeter precision. The transverse position is aimed with a pair of dipole magnets, whilst the longitudinal position of the Bragg peak is modulated by changing the beam energy.

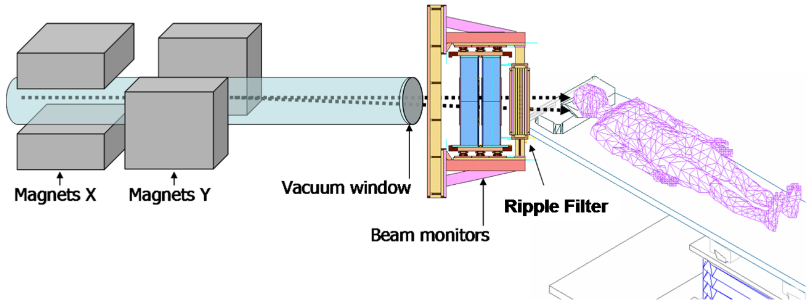

Figure 1. Beam delivery system including the scanning magnets , monitoring system and the ripple filter

With a synchrotron accelerator at each cycle the beam is ramped to a given energy. Typically a cycle lasts a few seconds and during the cycle the energy of the extracted beam is fixed. On the other hand with a cyclotron the Bragg peak can be displaced by degrading the beam energy with absorbers of different thicknesses. The energy changeover is then obtained with a mechanical operation which is timewise much shorter than a synchrotron cycle. Being the cyclotron a continuous machine the time required to perform the full treatment is almost independent on the number of energy switches.

With a synchrotron accelerator, even if it is possible to provide any number of kinetic energies, the constraint on the treatment time forces to reduce the number of energy steps. The problem is then to deliver a uniform longitudinal dose within specification with a small number of energy steps. This is especially true at the beginning of the accelerator operations when one has to deal with a limited set of available energies. The request can be satisfied by broadening longitudinally the peak of the Bragg curve with a ripple filter see ([ii,iii,iv]).

The idea of a ripple filter consists in defining a transfer function that, once applied to the hadron beams, favors a small spread around the Bragg peak and preserves a gaussian approximation of the shape near the maximum of the Bragg curve.

In this work it is reported the design and the simulation of the ripple filters for the beam delivery lines (BDL) of the CNAO (Centro Nazionale di Adroterapia Oncologica), which is located in Pavia, Italy. We discuss two applications: the first one is dedicated to proton beams and the second one is for carbon ion beams.

2. Monte Carlo beam delivery simulation

The beam has been simulated from the vacuum before the exit window (figure 1), through the BDL, and up to the water tank phantom. The BDL is composed by the monitoring system and the ripple filter. The monitoring system consists of an ensemble of ionization chambers with an equivalent water thickness of 1.1 mm. The ripple filter is placed right in front of the water tank at a distance of 50 cm from the isocenter.

The Monte Carlo simulation is implemented with Geant4.7.2[i] and it is linked to Root interface[i] which provides also an online follow-up of the events generated during the simulation. Parent particles are followed along the path as the energy degrades both for Coulomb and nuclear scattering up to the stopping point. Daughter particles, produced by fragmentation processes, are followed as well. Originally the goal of the simulations was the study of the effect of the monitoring system and of the ripple filter on the therapeutic beams mainly concerning the geometrical parameter of beam. We simulated both proton and carbon ion beams and we check for both beams the 3D distribution of deposited dose in a water tank. In this paper we discuss only the impact of the ripple filter.

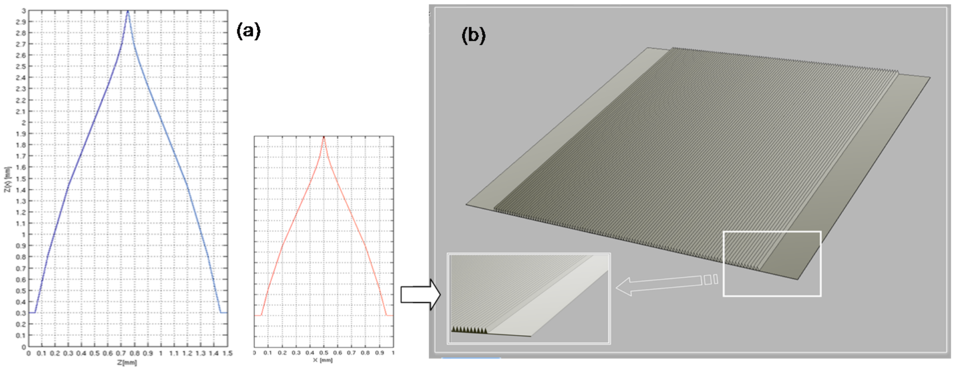

Figure 2. a) Sections of a ripple filter as described by Weber et al [??] of 2 mm and 3 mm, b) Ripple filter structure as implemented in the Monte Carlo simulation.

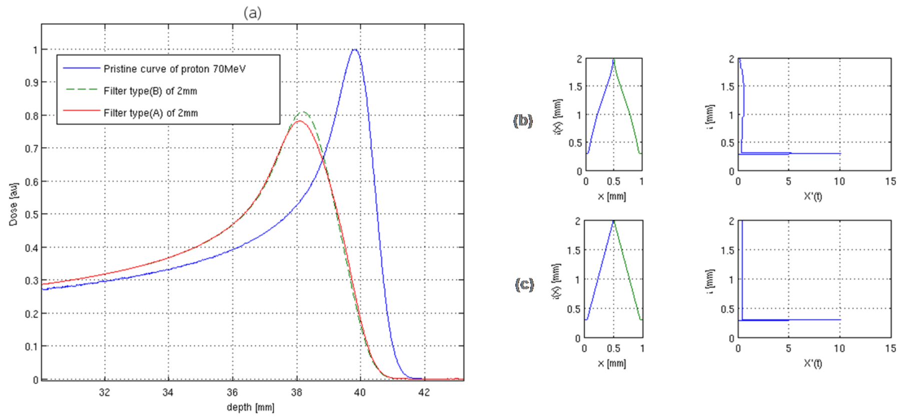

Figure 3. a) Comparison with the analytical method of the ripple filter type (B) as described by Weber et al. and type (A); b)-c) Section of ripple filter type (B) and (A) respectively and the corresponding transfer function $X'(t)$.

3. Method and materials

We designed two different shapes of ripple filters with similar dimensions. The first one (type A) has a simplified section (triangular section) and a thin base of plexiglass (200 mm × 200 mm × 0.3 mm) and a total thickness respectively of 2 mm and 3 mm (see Figure 3,c). The second shape (type B) has a sigmoidal section as described by Weber et al[ii] and reported in Figure 2 and 3,b. The sigmoidal shape of the type (B) filter satisfies the requisite of having a gaussian shape of the filtered Bragg peaks that permits the best uniformity when they are added up in a SOBP. Type (A) filter has a shape which can be easily machined and does not require special tooling.

In our study we used a plexiglass (PMMA) plates of 1.19 g/cm^3 density. The momentum spread for both protons and carbon ions was fixed at Δp/p = 0.05%.

The shape of the Bragg peak resulting from the passage of the ion beam through the BDL is strongly dependent on the scattering and the straggling processes that affect the final spatial distribution of the beam energy loss. In fact, as we will see in details in the following section, proton beams, that have higher straggling and scattering effects than carbon ions, are deflected and broadened easily and they are less sensitive to the precise shape of the ripple filter. Carbon ion beams needs more accuracy in the design and mechanical production of the ripple filter.

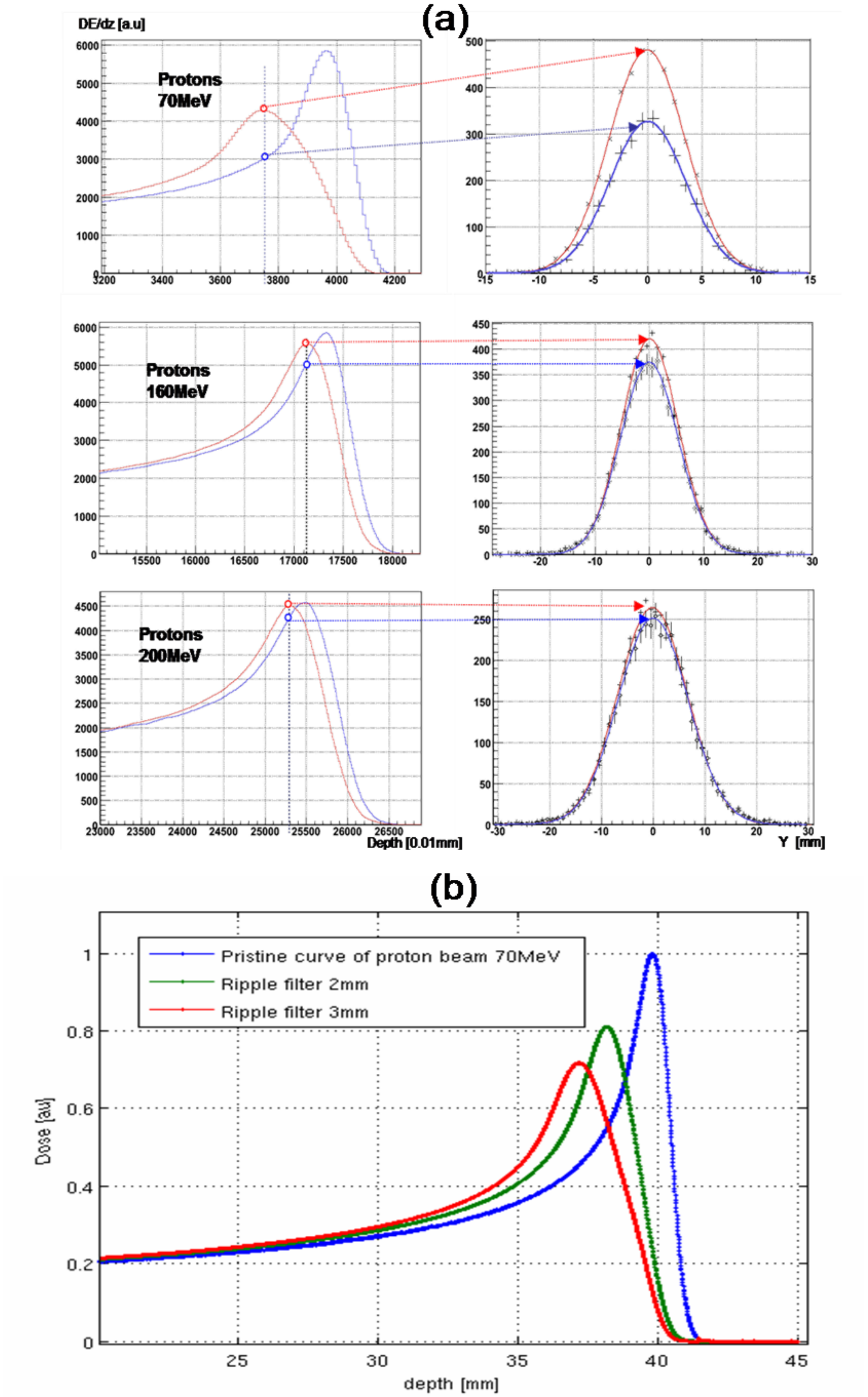

Figure 4. a) Comparison of the spreading of the Bragg peak with ripple filter type (A) respectively of 2 mm and 3 mm. b) Total energy loss in depth for proton beams of 70 MeV, without and with a ripple filter type (A) of 2 mm, and the corresponding lateral distribution at 37.4 mm (peak position with ripple filter).

3.1. Analytical pre-simulation

The full Monte Carlo simulation through the passive elements and the water phantom requires a fairly amount of CPU time, and the iteration over different shapes and dimensions of the ripple filter is a lengthy procedure. To shorten this time and get an approximated solution we studied an algorithm to solve analytically the problem. By convoluting the shape of the non-filtered Bragg curves with the filter transfer function one can predict the energy deposition curves as modified by the ripple filter. The transfer function was derived from the profiles of the ripple filters while the non-filtered Bragg curves were obtained from a Monte Carlo simulation of the full beam line and water phantom but without filter. With this technique, which has been briefly introduced, one can quickly estimate the effects of the different filter shapes for any given set of proton beam energies. Applying the method to the two types of filters (an example is reported in Figure 3) one can observe that the profiles of the filtered peaks are very similar and that the differences are less than 3% at the maximum dose.

In the next sections we discuss the impact of the ripple filters on the longitudinal energy deposition curves obtained with a full simulation for both proton and carbon ion beams.

4. Proton beams

In this study we considered only type (A) filters with total thickness of 2 mm and 3 mm respectively (see Figure 4,a). The tooling necessary to machine this type of filters is quite modest and this consideration has driven the choice. For different configurations we compared the longitudinal Bragg peak width (sigma), the beam width in the transverse plane, and the dose uniformity at the SOBP.

4.1. Variation of the width of the Bragg peak

The kinetic energies used in proton-therapy with active scanning covers the range between 70 and 250 MeV. As expected the present study shows that the effects of the ripple filter is more critical for low kinetic energies. At 70 MeV the sigma of the dose deposition curve along the beam direction is almost doubled by the insertion of the ripple filter, whilst the difference between 2 and 3 mm thick filter is of the order of 10%. For beam energies greater than 100 MeV the insertion of the ripple filter gives a marginal increase of the sigma (¡ 10%), which has already a value of several millimeters. The Bragg peak sigma values are reported for three different energies in Table 1. In the same table are given the widths for the 2 and 3 mm thick type (A) filters respectively. Even at low energies, the impact on the width of the peaks due to the two ripple filters is negligible (¡ 10%). However at 70 MeV the shape of Bragg peak falloff (see Figure 4,a) is quite affected by the filter, even if the width does not change by more than 10 %.

In Figure 4,b the longitudinal and transverse energy deposition curves are shown at three beam energies (70, 160, and 200 MeV) for a 2 mm thick type(A) filter and without filter. The energy deposition curves in the transverse plane with respect to the beam direction refer to the longitudinal position of the Bragg peak for the filtered case.

Table 1. Sigma values in [mm] from gaussian fits performed on a $\pm 1\sigma$ range around the Bragg peak

	70 MeV	160 MeV	200 MeV
No ripple filter	0.8	3	4.3
Ripple filter of 3 mm	1.9	3.3	4.4
Ripple filter of 2 mm	1.6	3.0	4.3

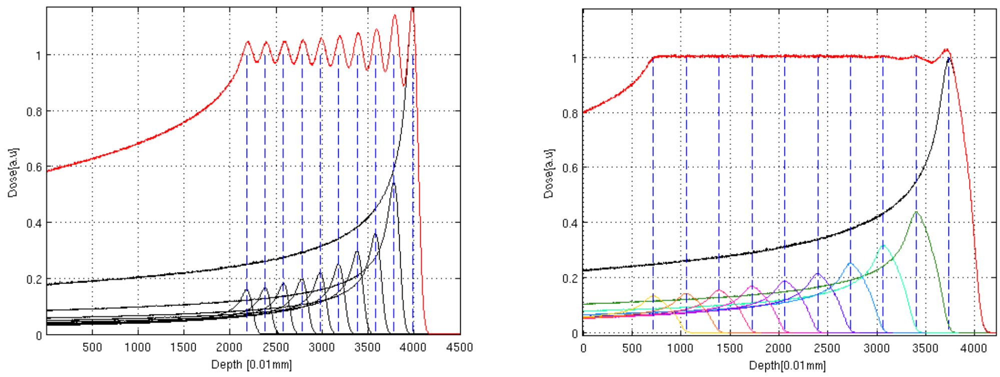

Figure 5. Spread out of the Bragg peak for proton beam of 70 MeV respectively without ripple filter and with ripple filter type(A) of 3 mm.

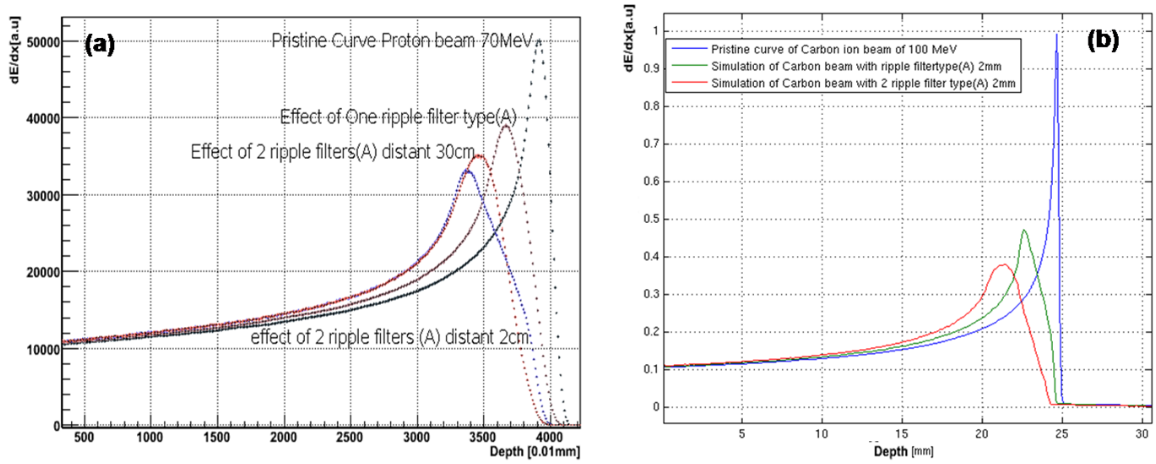

Figure 6. a) Geant4 simulations of energy losses as functions of depth for different setting of ripple filters in the proton beam path before the water tank; b) Comparisons between depth-dose curve simulated with respectively one and two ripple filters for carbon ion beam of 100 MeV/u.

4.2. SOBP dose uniformity

To evaluate the SOBP dose uniformity we overlap several curves as obtained with the simulation of a specific energy to mimick the dose delivery technique. Each curve has been displaced by a given amount with respect to the adjacent one and the dose delivered has been adjusted to obtain a flat average dose deposition. A sketch of the procedure is depicted in Figure 5 We used 10 different positions fixing the step between Bragg peaks as a function of the kinetic energy used.

With this technique we compared the dose uniformity on the SOBP with and without the ripple filter. The study was done with the ripple filter type (A) of 3 mm. For 70 MeV protons with the ripple filter and using a step of 3.36 mm the peak-to-peak dose uniformity is found to be ±1% error (see Figure 5). Without ripple filter the deviation increases to ±15% even if the step has been drastically reduced to 2 mm. The situation is less critic when the beam energy is above 100 MeV. In fact at 160 MeV, using the ripple filter we have a dose uniformity within $\pm 2\%$ and $\pm 3.5\%$ without filter for a scanning step of 6 mm both. For beam energy of 200 MeV the dose uniformity is not depending any more on the use of the ripple filter: we evaluated a peak-to-peak dose uniformity of $\pm 2\%$ with or without filter for scanning steps ranging from 3 mm to 7.6 mm.

5. Carbon ion beams

It is well known that for Carbon ion beams the Bragg peak is narrower than for the proton beams. Similar consideration applies also to the transverse plane. While for protons the effect of a deviation of the ripple filter shape from the ideal one tends to be washed out by the relatively large straggling, the Carbon ion Bragg curve is far more sensitive to the shape of the ripple filter.

Furthermore in the Carbon ion beam case it can be necessary to enlarge the Bragg peak width by using a configuration with two ripple filters.

5.1. Double filter study

To enhance the impact of the filtering on the widening of the Bragg peak we simulated a setup with an aligned double filter.

We compared the effect of different longitudinal positions and different way of coupling two type (A) ripple filters of 2 mm to optimize the conditions of the double filtering.

As shown the impact of the filter on proton beams is marginal above 100 MeV, thus we checked the effect of the double filter only at 70 MeV. In Figure 6 we compare the Bragg peaks obtained with a configuration without filter to several other configurations: type (A) 2mm thick single filter, and two same type double filter configurations. In one case the filters are 2 cm apart close to the patient and in another case one filter of the pair is placed right after the exit window and the second in front of the patient (30 cm apart). With a double filter the shape of the resulting Bragg peak is more regular and is a better approximation of a gaussian than the single filtered peak.

We deduce that one way to enlarge the Bragg peak preserving the gaussian shape of the peak with a ripple filter of type (A) is to use a double filtering where the first filter should be at the exit windows of the beam and the second one as far as possible from the first. This configuration corresponds to the convolution of two linear transfer functions giving as a results a non-linear transfer function.

5.2. Results

With Carbon ion beams, the energies clinically used and simulated in this study range from 100 MeV/u up to 400 MeV/u.

Similarly to what we did in section 5.1, we simulated a double filter, with the first filter placed just after the exit window and the second ripple filter at 30 cm from the first at the end of the monitoring system, right before the water tank. The two filters simulated are both of type (A) 2 mm thick. For comparison we investigated the single ripple filter setup which increases to about 1 mm the sigma at the Bragg peak at 100 MeV/u.

In Table 2) we see the effects of the simple and double filtering of the beam and the accuracy (normalized χ^2) of the gaussian fit. from gaussian fits performed on a $\pm 1\sigma$ range around the Bragg peak

From the normalized χ^2 of the fit and as expected the compatibility of the longitudinal dose deposition shape and a gaussian curve improves as the beam energy increase. But a good fit is obtained only with a double filter. Thus, for a Carbon ion beam we conclude that the configuration with double filtering results in a shape which is closer to a gaussian curve with respect to the single filter. With a separate simulation, we probed the single type (B) filter and

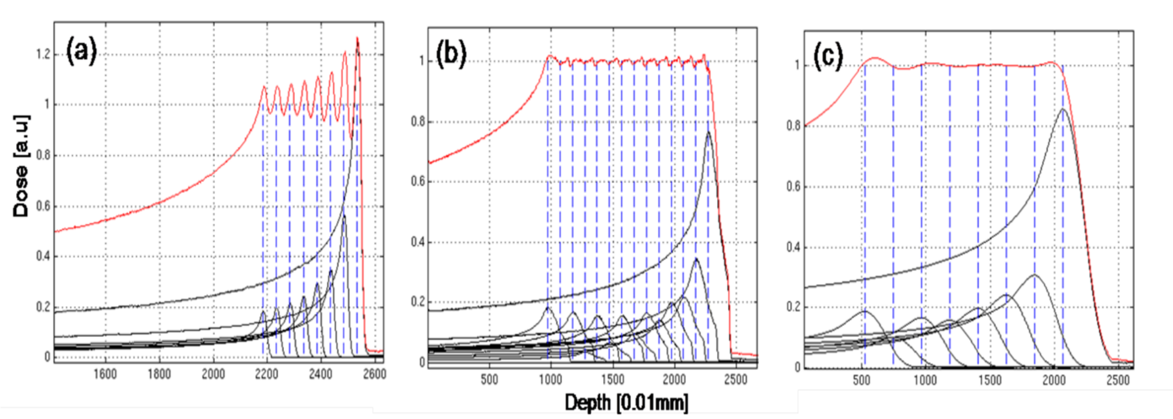

Figure 7. Spread out Bragg peak of carbon ion beam of 100 MeV/u with: (a) pristine Bragg curve using 8 spots at 0.5 mm step, (b) Bragg curve after passing through one ripple filter type (A) of 2 mm, using 14 single spots at 1 mm step, and (c) Bragg curve after passing through two ripple filters type(A) distant 30 cm, using 8 single spots with step of 2.2 mm.

Table 2. Sigma value in [mm] from gaussian fits performed on a $\pm 1\sigma$ range around the Carbon ion Bragg peak and the corresponding value of the normalized χ^2 of the fit.

	100 MeV/u	270 MeV/u	360 MeV/u
No ripple filter	0.2	0.7	1.1
σ (One ripple filter of 2 mm)	1.1	1.4	1.6
χ^2 (One ripple filter of 2 mm)	185	35	19
σ (Two ripple filters of 2 mm)	1.6	1.9	2.1
χ^2 (Two ripple filters of 2 mm)	26	2.6	1.0

we found results very similar to the double filtering with type (A). This observation substantiates the original hint that the filter shape, for Carbon ions, has a enormous impact on the resulting Bragg curve.

In Figure 7 we compare the SOBP profile for three different cases: a) no ripple filter and 0.5 mm steps; b) 2 mm type (A) filter and 1 mm steps; c) double 2 mm type (A) filter and 2.2 mm steps. One can clearly appreciate the improvement of the uniformity going from a) to c) even if the steps are increased from 0.5 mm to 2.2 mm.

6. Conclusion

In hadrontherapy the active scan technique requires the use of a filtering technique to reduce the number of energy steps necessary to match the tumour volume. In this study we compared several filter configurations adopting as a reference the shape described in **??** but the investigation focus on easy-to-machine shapes: we found that a triangular shape (type (A)) was a good compromise.

We conclude that 2 mm thick type (A) is adequate for low energy proton beams, while for protons above 100 MeV is not strictly necessary. In the case of carbon ion beams it is required a more structured solution like a double filter installed at a fairly large distance. A first investigation shows that the ripple filter type (B) and the double type (A) filter give comparable results, confirming that postion and shapes of the filters play an important role. Finally an analytical algorithm to quickly evaluate the impact of the filter is necessary, and in this paper it only has been only marginally introduced, to optimize the design of this vital part of the beam modeling system for active beam scanning with synchrotron accelerators.

7. References

[1] *Geant4 a simulation toolkit*(Nuclear Instruments and Methods in Physics Research A 506 2003) p 250303
[2] Weber U and Kraf G 1999*Design and construction of a ripple filter for a smoothed depth dose distribution in conformal particle therapy* (PMB volume 44 number 11) p 2765
[3] Takada Y, Kobayashi Y, Yasuoka K, Terunuma T 2004 *A miniature ripple filter for filtering a ripple found in the distal part of a proton SOBP* (Nuclear Instruments and Methods in Physics Research A 524) p 366
[4] Soukup M, Fippel M, Alber M 2005 *A pencil beam algorithm for intensity modulated proton therapy derived from Monte Carlo simulations* (PMB volume 50) p 5089-5104