

# BEAM INJECTION ISSUES OF FFAG FOR PARTICLE THERAPY

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## Abstract

Spot scanning irradiation is a novel and powerful scheme for particle therapy. The pulsed beam structure of FFAG (Fixed Field Alternating Gradient) accelerator is suitable for the scheme. In order to form a uniform dose distribution in a target volume, Beam intensity must be modulated in sync with beam energy modulation. The intensity modulation requires precise intensity control and constrain the bunch intensity of accelerator of pulsed beam structure. In the paper, injection related issue, that is the intensity modulation of FFAG accelerator, is discussed from the view point of spot scanning.

## INTRODUCTION

Particle therapy is recognized as an effective modality of radiation therapy with its better dose concentration and higher biological effectiveness compared to conventional x-ray therapy. For the therapy, particle accelerator which delivers high intensity beam is highly demanded. For such an accelerator, Fixed Field Alternating Gradient (FFAG) accelerator has received attention recently. FFAG can deliver particle beams with high repetition rate. Fixed field of the accelerator gives stability of beam quality and easy operation. Due to these attractive features, particle therapy facilities employing FFAG as main accelerator are being proposed and intensive R&D activities are under going[1, 2, 3].

## SPOT SCANNING AND FFAG

To exert the advantages of particle therapy, formation of conformal dose field is crucially important. For charged particle beam, range of mono-energetic beam has characteristic distribution, so called Bragg peak. It can provide well-defined dose field. On the other hand, it also requires precise energy control to obtain prescribed dose distribution. It makes the system more complicated compared to x-ray therapy.

Spot scanning irradiation is an ideal scheme to form a conformal dose field. In the scheme, target volume is divided into small unit volumes, "voxel". Then, each voxel is irradiated individually. The dose field is formed by the combination of horizontal beam sweep by fast magnet and energy modulation.

Forming a uniform dose field is an optimum scheme to provide sufficient dose in the target volume minimizing the unnecessary dose in normal tissues. Such a uniform dose field, Spread Out Bragg Peak (SOBP) is formed by superposition of energy modulated Bragg peaks. Figure 1 shows

an example of SOBP formation. The uniformity of the dose field required from treatment side is typically less than %. Due to the contribution of Bragg peak tail to the superposed dose, energy modulation requires intensity modulation as well. Such scheme, so called "Intensity Modulated Particle Therapy (IMPT)" is nowadays being investigated worldwide with conventional cyclotron or synchrotron, whose beam structure is continuous beam[4].

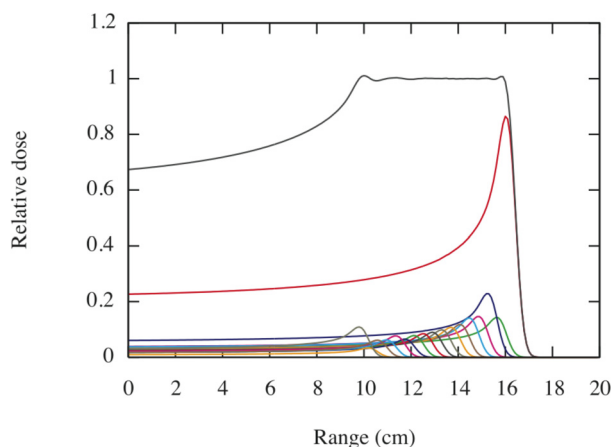


Figure 1: SOBP formation by superposing Bragg peak.

In applying IMPT with FFAG, beam structure is an issue. In FFAG, the beam circulated in the ring is extracted at a time. Thus, the extracted beam has pulsed structure. In the case, the intensity modulation is carried out in different manners from the case of synchrotron or cyclotron, whose intensity is controlled by changing the gate width of extracted beam.

In FFAG, two schemes can be considered for intensity modulation. One is to apply intensity modulation at the injection stage. It gives effectively higher beam current and resulting shorter treatment time, but requires complicated injection system. The other is to shoot a voxel with multiple bunches. It requires longer treatment time but the system can be much simpler than that of the former scheme. Thus, in the following study, the multiple bunch painting is employed from the realistic consideration as a treatment facility and the requirements for accelerator are discussed.

## INTENSITY MODULATION

Due to the range straggling, the shape of Bragg peak varies as the peak position varies. Therefore, to discuss intensity modulation quantitatively, dose distribution including its depth dependence must be given. The energy spread

of the extracted beam largely affects the dose distribution. Therefore, actually it has to be discussed for individual accelerator.

In discussing the requirements for the case of FFAG, as the first step, analytical model of Bragg peak distribution proposed by T. Bortfeld was employed[5]. Figure 2 shows typical dose distributions obtained with the model.

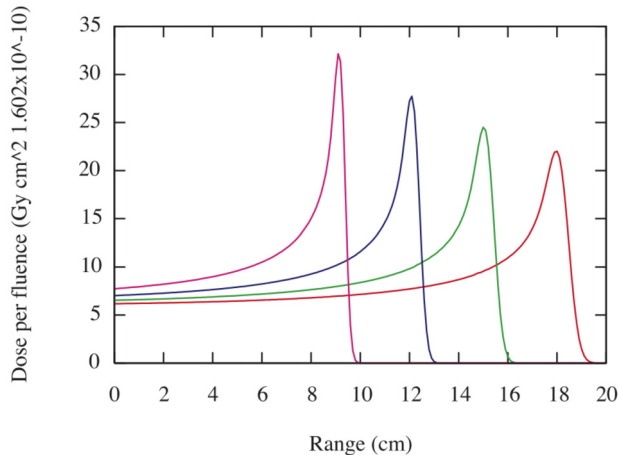


Figure 2: Typical Bragg peak using Bortfeld model.

Using the model, numerical optimization of intensity modulation was carried out changing the width and depth of SOBP. In the calculation, the depth dependence of the Bragg peak width was taken into account.

For the evaluation of the uniformity of SOBP, quality factor,  $Q$ , is introduced.

$$Q \equiv \frac{D_{max} - D_{min}}{D_{avr}}, \quad (1)$$

where  $D_{max}$ ,  $D_{min}$ , and  $D_{avr}$  mean maximum, minimum and average of dose in the SOBP region of interest, respectively.

Figure 3 and 4 show an example of SOBP obtained using the numerical scheme and an example of weight of intensity modulation, respectively.

Table 1 summarizes the characteristics of examined SOBPs. The result indicates that the energy step size should be finer than 1MeV in order to carry out spot scanning. In the FFAG for proton therapy, typical energy gain is 200 keV/turn in the case of 1 kHz operation. Even such high repetition rate, the energy step size for FFAG can be smaller than the clinical requirement. It also indicated that even for the widest SOBP, 13cm, to form SOBP, on average 8 pulses per voxel is required in the case of 1/100 intensity quantization. (The influence of quantization is to be discussed in the following section) It means with the repetition rate of 1 kHz, more than 100 voxels per second can be irradiated.

In the study described above, it is assumed that the intensity can be controlled arbitrarily. However in real situation, especially with the pulsed beam of FFAG, actual intensity modulation is inevitably quantized. For FFAG, the size of

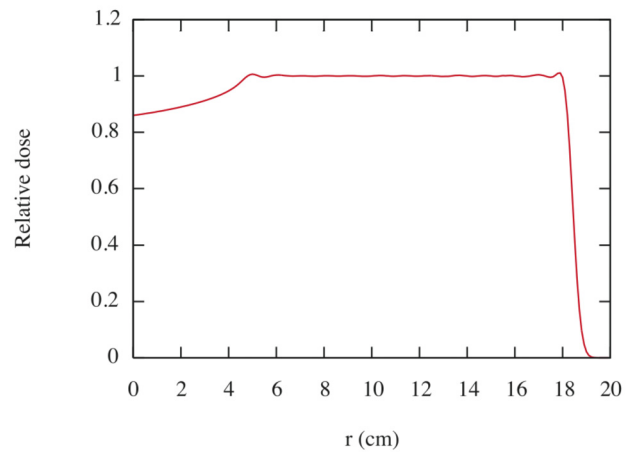


Figure 3: Typical SOBP after optimization (width=13cm).

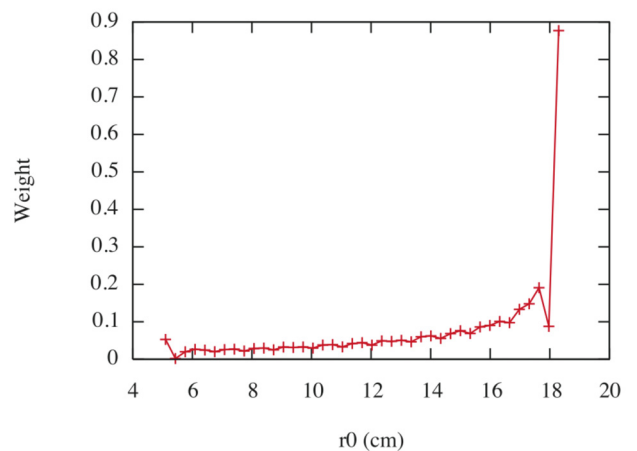


Figure 4: Typical weight of intensity of SOBP after optimization (width=13cm).

beam quantization determines the beam intensity of single bunch. In order to evaluate the minimum bunch intensity, the influence of quantization to the dose uniformity was investigated by quantizing intensity step size of the optimization process. Table 2 summarizes the influence of the quantization to the uniformity of SOBP. From the above results, to form a dose distribution with an uniformity of  $\pm 2\%$ , intensity modulation with a precision of 1% is required.

The studies presented above has several points to be improved.

- The procedure of SOBP optimization is based on numerical fitting with iteration and basically model-independent. Including the analytical procedure with minimum assumption of Bragg peak shape, that is 'sharp peak with long tail', more precise optimization can be expected.
- In the optimization, the separation of Bragg peak was set constant. However, real Bragg peak width has depth dependence. Thus, introducing the depth-dependent Bragg peak separation into the optimizing

Table 1: Summary of energies and weights required to produce the SOBPs.

SOBP width (cm)	SOBP range (cm)	$E_{min}$ (MeV)	$E_{max}$ (MeV)	$\Delta E_{min}$ (MeV)	Max Weight	Min Weight	No of Peaks	Average no. . pulse/voxel <sup>1</sup>
13	5-18	73.4	150.7	1.9	0.020	0.939	34	8
7	10-17	108.1	146.0	1.8	0.088	0.947	20	12
	2-9	44.3	102.8	1.2	0.0067	0.900	39	8
2	13-15	125.0	136.3	1.8	0.056	0.901	7	25
	9-11	101.8	114.6	1.5	0.017	0.911	9	21
	5-7	73.7	89.0	1.2	0.059	0.966	12	17

Table 2: Summary of quantization effect on the uniformity of SOBP.

Quantization Min. Weight	Q(%)					
	5-18 cm	10-17 cm	2-9 cm	13-15 cm	9-11 cm	5-7 cm
-	2.52	1.69	2.90	2.47	2.97	2.60
0.01	3.10	1.89	3.42	4.06	3.77	2.58
0.02	5.48	2.92	6.67	4.24	4.43	2.74
0.05	18.40	7.50	18.90	3.18	7.79	5.52
0.1	46.40	27.80	56.40	6.64	8.95	10.8

procedure will improve the dose field uniformity. For it, semi-analytical procedure mentioned above will help.

- In the real treatment, to suppress the dose level in the normal tissues of incident side is also important issue. With the tail of Bragg peak, too sharp Bragg peak could potentially increase the irradiation in the normal tissue. From this point of view, optimization of Bragg peak width can be considered. It would relate to an optimum energy spread of the delivered beam.

These issues remain as items for future study.

## REQUIREMENTS FOR ACCELERATOR

From the study of intensity quantization, the minimum bunch intensity can be evaluated. Assuming that single voxel is painted by single Bragg peak. From the Bragg peak model used in the study, typical energy deposit of mono-energetic proton of 18cm water-equivalent range in unit voxel is 10MeV/particle. In the widest SOBP examined, 13cm, the highest Bragg peak gives ~ 90% contribution at the deepest range of the SOBP. Assuming typical voxel size for spot scanning as 5mm × 5mm × 5mm, in order to provide 1Gy(1J/kg) dose to the voxel, the required number of proton is

$$\frac{1[J/kg] \times (0.5^3 \times 10^{-3})[kg] \times 0.9}{10 \times 10^6[eV] \times 1.602 \times 10^{-19}[J/eV]} = 7 \times 10^7 \quad (2)$$

To achieve uniformity of ±2%, 1% of quantization is required. Thus, the unit bunch intensity per 1Gy is  $7 \times 10^5$ . Prescribed dose for one fraction would not exceed 5Gy. Thus, the minimum required bunch intensity is order of ( $10^6$ ) proton/bunch. For a bunch intensity of proton accelerator, such intensity is quite small number. Therefore,

for FFAG of particle therapy application, beam monitoring system and intensity control at the injector stage are crucially important.

## SUMMARY

Using an analytical model of Bragg peak, requirements for accelerator in the case of spot scanning are investigated. The results are

- Intensity modulation of 1/100 precision is required to achieve dose uniformity of ±2%.
- Even with the widest dose field, ~13cm, the average pulse/voxel is less than 10. It means with 1kHz operation, more than 100voxel/sec can be irradiated.
- To carry out spot scanning using FFAG, the unit bunch intensity is ~  $10^6$  proton/1Gy. Such low intensity makes the development of monitor and control system crucially important for the medical-purpose FFAG.

## ACKNOWLEDGEMENT

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