

# ACCELERATOR DEVELOPMENT FOR ADVANCED PARTICLE BEAM THERAPY

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## Abstract

Particle beam therapy has become one of the most effective modalities of cancer treatment. High reliability, high throughput and high-precision irradiation are strongly demanded for the therapy system. In order to meet the requirements, we have developed several key technologies of synchrotron-based accelerator system, such as multi-harmonic RF acceleration, extracted beam intensity feedback, respiration-synchronized operation and beam tuning for spot scanning irradiation. Most of these technologies have already been applied to the proton beam therapy system at M.D. Anderson Cancer Center. Beam specifications required for spot scanning irradiation have been achieved successfully. In this paper, present status of the accelerator development is described.

## INTRODUCTION

Hitachi has developed one of the most advanced proton beam therapy (PBT) systems. This system was first installed at the Proton Medical Research Center (PMRC) at the University of Tsukuba in Japan [1]. Based on considerable experience and expertise gained at PMRC, Hitachi designed and built a second PBT system at the University of Texas M.D. Anderson Cancer Center (MDACC), which is one of the world's largest cancer treatment and research centers.

Recently, high reliability, high throughput and high-precision irradiation are strongly demanded for particle beam therapy, and the same is true in the case of MDACC. In order to increase the throughput of treatment, a higher extraction beam current should be required for the accelerator system to attain a higher irradiation dose rate. As for high-precision irradiation, the accelerator system must enable gated-beam irradiation synchronized with patient's respiration and spot scanning irradiation by fast beam modulation (on/off) technology. And besides, cost reduction is also an important subject for study as an equipment manufacture. Hitachi has hence developed several key technologies of synchrotron-based accelerator system to meet the above requirements.

In the following sections, we describe notable features of the Hitachi PBT accelerator system, by presenting typical beam test results at MDACC, experimental results from collaborative research ongoing at PMRC, and those from our laboratory tests.

## SYSTEM CONFIGURATION

Equipment layout of the Hitachi PBT system installed at MDACC is shown in Fig. 1. It consists of a 7MeV injector linac, a compact synchrotron, a high-energy beam

transport line, four treatment rooms and an experimental room. Three of the treatment rooms have each iso-centric gantry and the other one has two horizontal fixed beam ports. Spot scanning irradiation has been implemented in one of the gantry treatment rooms, and passive scattering irradiation has been adopted for all the other beam ports.

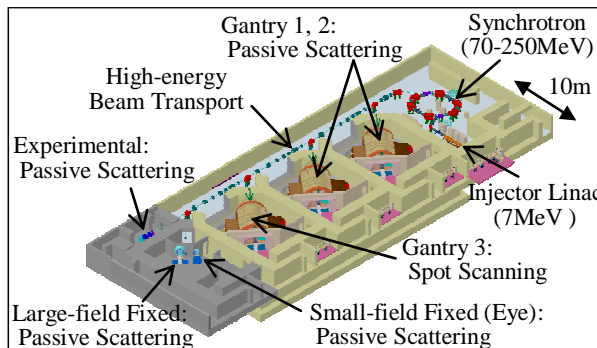


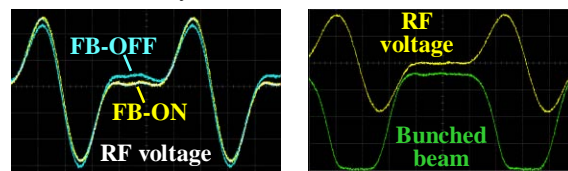
Figure1: Hitachi PBT system installed at MDACC

## SYNCHROTRON

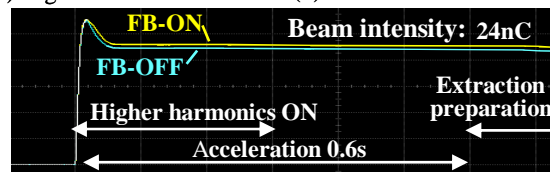
The proton synchrotron employs a separated-function FODO lattice of two super-periods with a circumference of 23m. The lattice design was previously reported [2]. The extraction beam energy can be changed between 70-250MeV at each operation cycle, and the repetition rate is also variable between 0.1-0.5Hz for spot scanning and/or respiration-synchronized operation.

### RF Acceleration

After multi-turn injection, the coasting beam stored in the synchrotron is adiabatically captured into a bunch and accelerated up to the maximum energy with a tuning-free wideband RF cavity loaded with FINEMET cores [3].



(a) Higher harmonics feedback (b) Bunched beam waveform



(c) Temporal evolution of circulating beam intensity

Figure2: Multi-harmonic RF acceleration

As already reported in detail [4], we have developed a multi-harmonic RF acceleration system to mitigate space-

charge effects in low energy region, in order to achieve a higher intensity of extraction beam required for passive scattering irradiation over a large volume in a short time. At MDACC, the circulating beam intensity was enhanced by a factor of 1.8, and successfully reached 24nC/pulse ( $1.5 \times 10^{11}$  ppp) after acceleration by using some other RF manipulations as well. See Fig. 2. The RF acceleration system plays an important role in preparation for beam extraction, such as optimizing the bunching factor and the momentum spread to stabilize the circulating beam and realize a smooth extraction beam spill.

### Beam Extraction

The accelerated beam is extracted by the transverse RF driven slow extraction scheme (RFDE) using a horizontal third-order betatron resonance [5]. In this RFDE scheme, the separatrix of the nonlinear resonance is kept constant and the transverse RF perturbation with a narrow frequency bandwidth is applied to make the circulating beam diffuse to and beyond the separatrix. Therefore, high stability of the position and gradient of the extracted beam is easily obtained and the fast intensity modulation (or beam switching-on/off) is possible by modulating the amplitude of the transverse RF perturbation, which are indispensable for spot scanning irradiation. To date, the stably attained intensity of the extracted beam has reached 18nC/pulse ( $1.1 \times 10^{11}$  ppp) at MDACC.

So far, the time-structure of the extracted beam spill has been tuned by pre-programming the amplitude and the frequency spectrum (center frequency, bandwidth, etc.) of the transverse RF perturbation. We have hence developed a feedback system to control the extracted beam intensity automatically, in order to accurately create the desired spill waveform within a short time. Typical experimental results obtained at PMRC are shown in Fig. 3. The control accuracy within  $\pm 5\%$  and the rise time within 1ms were simultaneously attained by PID control.

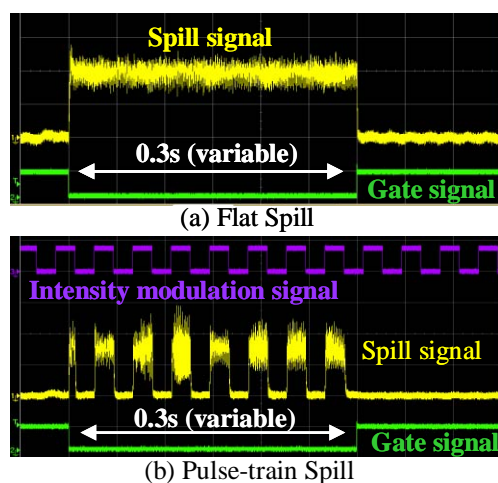


Figure3: Extraction spill created by feedback

### Respiration Synchronization

The synchrotron can be operated fully synchronized with patient's respiration. After the end of acceleration, the synchrotron waits for an extraction enabling signal

sent from the respiration monitor during 5s at maximum. When it is received, the extraction sequence starts and the circulating beam is extracted for 0.5s at maximum. The extracted beam can be terminated quickly by turning off the transverse RF perturbation, when the extraction enabling signal is disabled. After the end of extraction, the synchrotron begins deceleration, and restarts injection and acceleration sequentially. Even in the respiration-synchronized operation, the accuracy of beam position is kept within  $\pm 0.3$ mm at the irradiation point.

## INJECTOR LINAC

The 7MeV injector linac with a debuncher is fabricated by AccSys Technology, a subsidiary company of Hitachi. The proton linac consisting of a 3.5MeV RFQ followed by a DTL is 4.5m in total length and supplies an injection current of 10mA. Although the present linac employs a filament-type ion source called duo-plasmatron, we have alternatively developed a compact microwave ion source utilizing permanent magnets from the viewpoint of high reliability, high stability and maintenance-free. An output proton current of 50mA has been stably achieved from the microwave ion source [6].

## BEAM TRANSPORT AND GANTRY

The proton beam extracted from the synchrotron is transported to the irradiation point of each iso-centric rotating gantry or each horizontal fixed beam port. A fishbone structure of the high-energy beam transport line (HEBT) has been chosen for modularity and easy tuning. All the gantries can be rotated  $\pm 190^\circ$ , and the accuracy of mechanical iso-center was confirmed at MDACC within a sphere of 1mm in diameter for all the rotating angles. All the magnets employed for the HEBT and the gantries are made of stamped laminated steel to obtain reproducibility of magnetic field and shorten the switching time of beam energies and courses. At MDACC, the beam courses were switched within 1min without any problem as shown in Fig. 4. The switching time of beam energies of 2.2s was also realized in energy-scan operation for spot scanning.

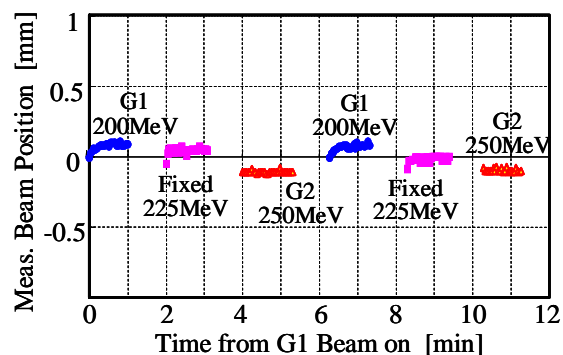


Figure4: Fast switching of beam courses

The function of automatic beam tuning (ABT) has been implemented to correct the beam position and gradient at the entrance of each gantry and at each irradiation point. The ABT is a batch of iterative sequence control, in which

pair of steering magnets upstream of each correction point is excited according to the beam positions detected with two monitors on the same drift line where the correction point exists [7]. The ABT shortened commissioning time.

A beam abort system with a kicker magnet and a beam dump has been installed in HEBT to shield the unintended beam. The beam abort system plays an important role in case of an emergency.

### SPOT SCANNING IRRADIATION

In spot scanning irradiation, a three dimensional shape of tumour is divided in depth direction into a lot of two-dimensional layers, and each thin layer is further divided in two orthogonal lateral directions into a large number of small volumes called irradiation spots. In depth direction, each layer is selectively irradiated by changing the beam energy extracted from the synchrotron (energy-scan). In each layer, the irradiation beam is deflected to one of the target spots with a pair of scanning magnets. The beam irradiation is kept on until the prescribed dose is attained for the target spot, while the excitation current of the scanning magnets are fixed. At the time the prescribed dose is attained, the beam irradiation is stopped rapidly and the scanning magnets start changing the excitation current toward the next target spot. During the transition, the irradiation beam must be shielded. See Fig. 5.

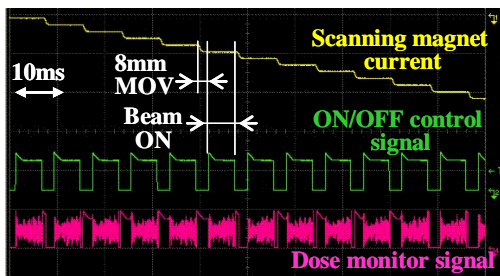


Figure5: Sequence of spot scanning irradiation

Thus, other than high stability of the beam position and size, fast switching-on/off, especially, fast and thorough shutoff of the irradiation beam is necessary to realize the dose uniformity required as the clinical specification. As for the beam position stability, the synchrotron bending magnets are equipped with slits to reduce eddy current effects and operated under the optimized initialization pattern of the exciting current to suppress hysteresis effects. The beam size stability is ensured by the RFDE scheme and optimization of the momentum spread to stabilize the circulating beam. The fast beam on/off is attained by switching on/off the acceleration RF voltage synchronized with the transverse RF perturbation for beam extraction [8].

At MDACC, the measured accuracy of the beam position on the iso-center plane was within 0.5mm in radius as shown in Fig. 6. The measured variation of the beam size observed with a profile monitor located at 0.9m above the iso-center was within  $\pm 0.5$ mm. The in-depth dose distribution with intended spread-out Bragg peak (SOBP) was precisely created by energy stacking method

(synchrotron energy-scan), as is shown in Fig.7. The required dose uniformity within  $\pm 3\%$  was successfully achieved over the specified target volume in the maximal irradiation field area of 30cm $\times$ 30cm.

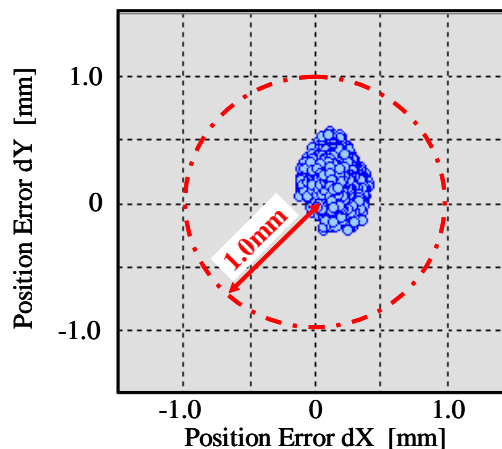


Figure6: Beam position accuracy on the iso-center plane

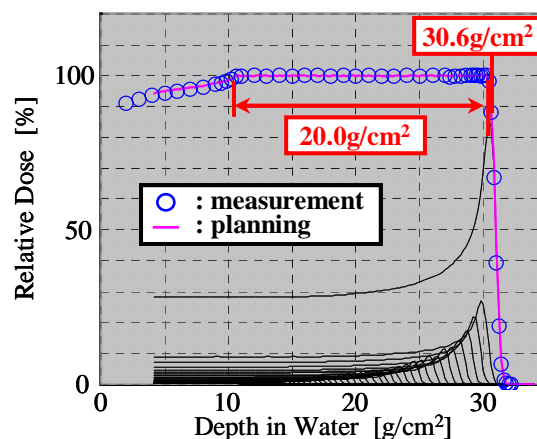


Figure7: Spread-out Bragg peak created by energy stacking

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