Beam Commissioning of Synchrotron Ring at Hyogo Ion Beam Medical Center

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Abstract

Beam commissioning of the synchrotron at Hyogo Ion Beam Medical Center started on March 2000. The requirements for the beam has been successfully attained. Regular operation for clinical trial has been carried out since May 2001.

1 INTRODUCTION

The synchrotron at Hyogo Ion Beam Medical Center[1] was designed to provide proton, helium and carbon beams whose required intensity is 5Gy/min at the end of the high energy beam transport line. The injection energy is 5MeV/u for all the beam species. The extraction energy range are 70 - 230MeV/u for proton and helium, and 70 - 320MeV/u for carbon. Corresponding range of magnetic rigidity is 0.3235 - 5.576Tm. A third integer resonance is used for the slow beam extraction. The ring has 6-fold symmetry(Figure 1); each superperiod consists of two regular FODO cells(Figure 2). Operating tunes are (3.69, 3.14) at the injection and (3.67,3.12) at the extraction as shown in Figure 3. The main parameters of the synchrotron are shown in Table 1

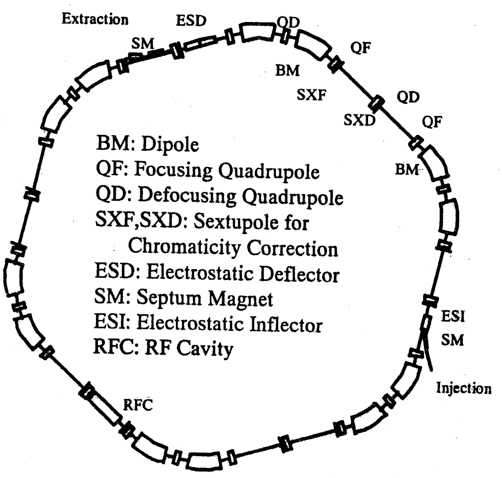

Figure 1: Layout of the Synchrotron.

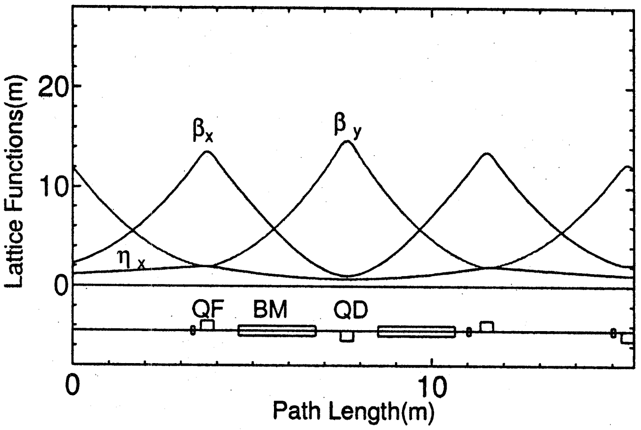

Figure 2: Lattice Functions.

Extraction energy	70 - 230 MeV/u (p, He) 70 - 320 MeV/u (C)
Beam intensity	7.2e10pps (p) 1.8e10pps (He) 1.2e9pps (C)
Repetition rate	0.25 - 1Hz
Circumference	93.6m
Symmetry	6-fold
Structure	FODO
Number of cells	12
Operating point	(3.69,3.14) injection (3.67,3.12) extraction
Harmonic number	3
RF frequency	0.993 - 6.417 MHz
RF Voltage	5.2kV(3kV operation)
Number of bending magnets	12 (+1 for monitor)
Number of quadrupole magnets	24
Bending field	0.076T - 1.324T

Table 1: The main parameters of the synchrotron.

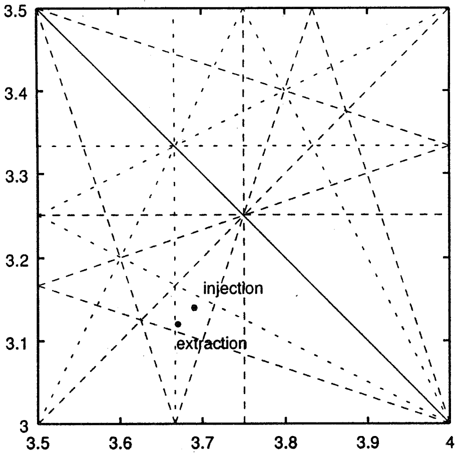

Figure 3: Operating Point.

2 BEAM COMMISSIONING

2.1 *Excitation pattern of magnets*

Prior to practical beam commissioning, excitation patterns of pulse magnets had been made using data from magnetic field measurements. We assumed that the field as a function of the excitation current can be fitted to the polynomial functions. Fifth order polynomials are used for main dipoles, main quadrupole and sextupoles. These functions realize good agreement even in low and high field region where remanent and saturation effects are signifiacat respectively. Other magnets i.e. bumpers, steerers and correction quadrupoles are fitted to 2nd order polynomials. Field measurements were done by using long coil. Thus, in the case of main dipole, we obtained Bl as a function of I represented as

$$Bl(I) = \sum_{i=0}^{5} a_i I^i. \qquad (1)$$

All the patterns are produced on a computer as data points. A pattern has data points corresponding frequency of 1440 Hz. Data sets are sent to the man-machine-interface(MMI), then it is modified if necessary by an operator and sent to VME controller which is connected to each magnet power supply[2].

During ramping of the magnets, RF frequency of the accelerating cavity is varied by a B clock counter. One count of the B clock corresponds to 0.2 gauss in the bending field measured by using a reference bending magnet in the power supply room.

2.2 *Beam Injection*

We started beam commissioning from helium beam. The first turn beam injection was observed by using faraday cup at right up stream of the injection septum inflector without changing any parameters from the design values.

A multi-turn injection is performed with four bump magnets. Injection beam and pulse of the bump magnets are shown in Figure 4. Nominally 200μs pulse is injected. The injection efficiency is calculated as 35%.

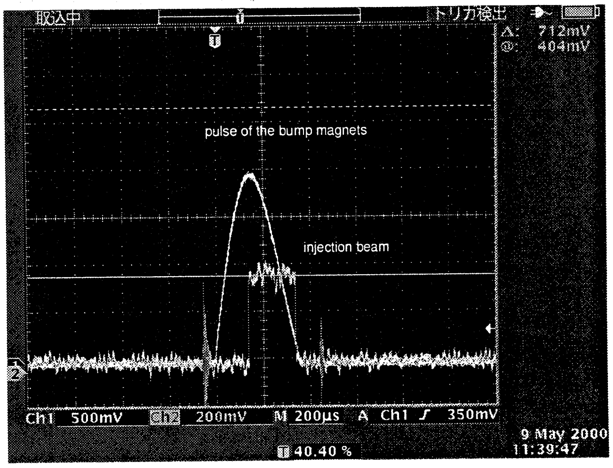

Figure 4: Injection beam and pulse of the bump magnets.

2.3 *RF Acceleration*

The frequency of RF acceleration is determined by the circumference of the ring, energy of the beam and the mass. The f_{rf} for the flat top and the flat bottom which are called t-clock regions are set to constant frequencies. In the acceleration and deceleration regions which are called b-clock regions, the frequency patterns are determined by the derivative of the bending magnet field. The RF cavity is ferrite loaded tuned type. The harmonic number $h = 3$. The minimum frequency is 0.993MHz which corresponds to 5MeV proton beam, and the maximum is 6.417MHz for 320MeV carbon beam. For t-clock regions, we give appropriate frequencies from the MMI terminal. On the other hand, for b-clock region, data array of frequency as a function of BM field is provided. The pointer of the array is incremented if one pulse comes from the b-clock pulse generator which generates a pulse when the magnetic field is changed by 0.2 gauss. The initial value of the frequency in the b-clock region is chosen so that the difference from the frequency in the t-clock region takes minimum. At the transit from b-clock to t-clock, if there is a frequency gap, they are connected linearly at a fixed rate. It has been set to 2.8kHz/ms.

The RF frequency and the bending field at the flat bottom is adjusted for the injector energy so that the incident beam can circulate at the center of the beam duct. At the flat top, assuming that circumference of 93.6m is correct, the RF frequency is calculated for each required extraction energy. Then we determine the bending field so that the orbit is at the center. At this time, COD should be corrected. To measure COD 12 horizontal and 11 vertical beam position monitors are used. And to correct COD 12 horizontal and 12 vertical steerers are used. All the quadrupoles except for one QD at the beam extraction section has a set of a BPM and a steerers in the neighborhood[3]. By the best corrector method, COD at the maximum of 25mm has been successfully corrected to the maximum of 2mm at the flat bottom and 5mm at the flat top.

The beam is captured 3.5ms after injection changing the RF voltage from 0V to 200V within 0.7ms. The RF voltage is kept at 200V until smoothing starts. It raise up to 3kV during 50ms smoothing, and is hold at 3kV all the time region after smoothing ends. The capture voltage and the maximum voltage have been optimized from precise beam tuning to minimize beam loss. Capture and acceleration efficiency is summarized in Table 2. In the case of 320MeV carbon, a typical beam signals are shown in Figure 5.

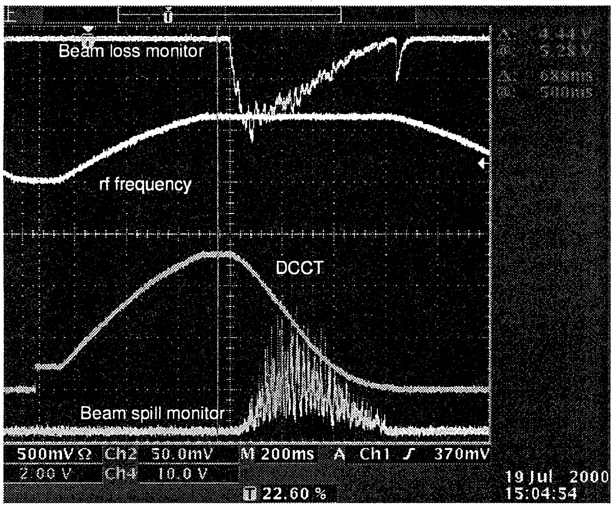

Figure 5: Typical acceleration and beam extraction figure for 320MeV/u carbon beam.

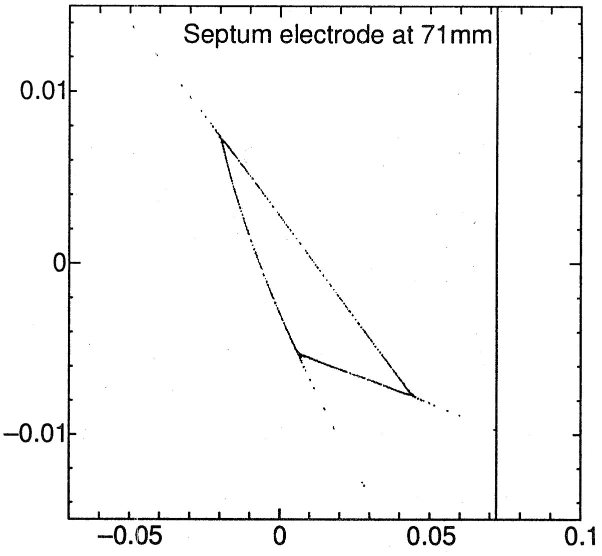

Figure 6: The optimized separatrix obtained by beam tuning.

Table 2: The efficiencies of RF capture, acceleration, extraction and the number of particles for each beam species.

Beam	Energy MeV/u	Cap. eff. %	Acc. eff. %	Ext. eff. %	Number of particles pp
Proton	150	50.9	83.5	89.6	7.62×10^{10}
	190	51.9	89.0	81.9	7.56×10^{10}
	230	49.1	91.7	91.4	8.85×10^{10}
Carbon	250	88.9	91.1	98.5	3.62×10^{9}
	320	86.4	92.6	82.6	3.95×10^{9}

2.4 Slow Beam Extraction

The beam is extracted from the ring by using third order resonance slow extraction method to obtain spill length of 400ms. The natural chromaticity of (-4.1,-3.0) has been corrected to (-0.2,-5.8) by focusing sextupole SXF. For the tuning of beam extraction, main focusing quadrupole QF, resonance exciter SXFr, SXDr and orbit bumper BMP1-4 are utilized to adjust the separatrix in the phase space. Figure 6 shows the optimized separatrix obtained after the tuning. It is the case of 150MeV proton beam.

The extraction efficiency and the number of particles for each beam species are shown in Table 2. These were measured at the beam stopper installed in the high energy beam transport line.

2.5 Daily Operation

Machine operation for clinical trial has been carried out since May 2001. It is run by two operators. They are performing not only the synchrotron but operation of the injector or beam transport systems. Adjustment for the synchrotron is usually unnecessary. On the other hand, in gantry rooms, a drift of the beam axis exceeding the tolerance of 2mm occurs occasionally. Then it is made within the tolerance by adjusting the steering magnets in the transport line.

3 SUMMARY

In Heavy Ion Beam Medical Center, three kinds of protons, two kinds of carbon, and a total of five kinds of operation patterns are performing supply operation for clinical trial. The beam intensity of 2 Gy/min has been attained for every operation pattern. Operation with the intensity up to 5Gy/min has been permitted since April 2001. Because the reproducibility of the machine is good, daily adjustment is almost unnecessary.

REFERENCES

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[3] Y. Yamamoto, et al., Proc. 12th Symposium on Accel. Sci. Tech. Wako, Saitama, Japan(1999), pp.507-509.