# Design Study of Compact Proton Synchrotron for Biomedical Use

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*Abstract*

A proton synchrotron which can accelerate protons up to 370 MeV with the beam current of 10 nA is studied assuming the existing 7 MeV linac as its injector. New techniques of slow beam extraction and beam transport of variable energies can be studied in the ring.

## 1. INTRODUCTION

At Kyoto University, π-meson research center plan has been proposed in these several years[1]. It is planned for wide variety of fields as nuclear, elementary particle and solid state physics and medical application including pion therapy. The accelerator complex consists of an 800 MeV proton linac with the average current of 200 μA and a compressor ring and a 25 GeV proton synchrotron with the average current of 50 μA as shown in Fig. 1.

As the preparatory work for the project, accelerator development is made at Institute for Chemical Research (ICR), Kyoto University. A linear accelerator consisting of an RFQ and a drift tube linac (DTL) of Alvarez structure both with operation frequency of 433 MHz has already been constructed[2]. It is accelerating the proton beam up to 2 and 7 MeV with the RFQ and DTL, respectively. Recent result of its performance is separately presented at this conference[3]. Thus the accelerator system has proved that the compact proton linac with higher frequency as 433 MHz can be well applied for the π-meson research center plan as a low energy section. A coupled cavity linac for high energy section is left to be tested with beam, while its low power study has already been done[4].

In addition to the accelerator development, the 7 MeV proton linac is also to be utilized to provide a new capability of interdisciplinary use for researchers of chemistry, biology and material sciences in the institute. Furthermore

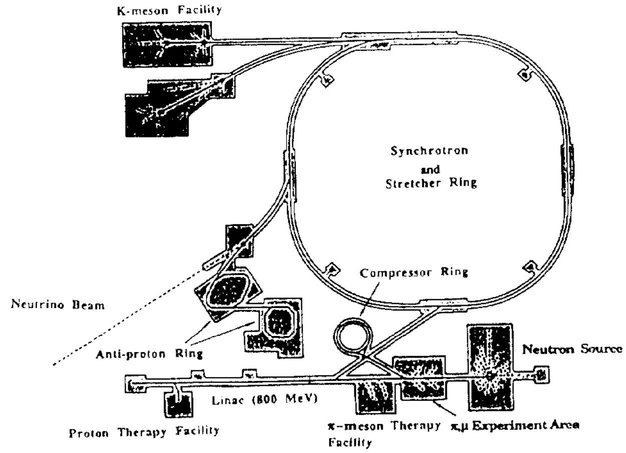


Fig. 1 Layout of π-meson Research Center.

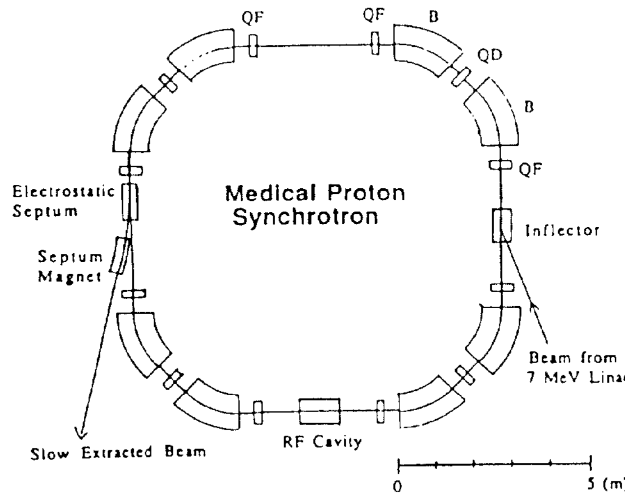


Fig. 2 Layout of the Proton Synchrotron for ICR

proton therapy has come to be pursued as the first phase also at Kyoto University stimulated by its lower cost and good success at Loma Linda University[5] and Tsukuba University[6].

As candidates for the accelerators dedicated for proton therapy, there might be several schemes such as a compact cyclotron[7], a linac operated with high frequency[8] and a proton synchrotron. They have their own merits and demerits[9]. From the point of view of providing beams with variable energy without usage of an energy degrader, a proton synchrotron is considered to be preferable.

In our case, the possibility of adding a small proton synchrotron which can be also used as a storage ring to shape the beam spill time, is studied. In Fig. 2, a schematic layout of the ring is shown. Important role of this ring is to provide a playground for research and development works needed for construction of a dedecated machine for the proton therapy.

## 2. BASIC DESIGN OF THE SYNCHROTRON

As the accelerator for proton therapy, beam of the energies in the range of 70~250 MeV is required. The intensity of the order of 10 nA is needed. In order to realize such facility in a limited site, the one constructed at Loma Linda University is an extream example. However, our ring is, as mentioned above, not a dedicated machine but is mainly to be used for another users in chemistry, biology and material sciences. So it is not so important to make the ring compact, but some flexibility is needed. Its mean radius is 5.3 m and betatron tunes in horizontal and vertical directions are 1.75 and 1.25, respectively. The layout of the ring is shown in Fig. 2. In Fig. 3, beta and dispersion functions are shown for the one superperiod of the ring. In Table 1, the main parameters of the ring is listed up.

The magnetic field of the dipole magnets is 1.2 T for 250 MeV protons and if this field can be raised to 1.5 T, which is not so difficult, the maximum energy can be raised up to 370 MeV, at which energy π meson can be produced although the intensity is not so high. The repetition rate of the synchrotron is designed to be 0.5 Hz for the excitation energy up to 250 MeV and required dI/dt is 5740 A/sec. In order to keep the voltage required for power supply at the similar level, dI/dt is kept the same as this value for the excitation up to 370 MeV, which needs a little longer rise time of 0.64 sec., but does not change the repetition rate if we restrict the flat top time a little bit.

For the above condition, dB/dt is 2.02 T/sec and necessary energy gain per turn is 137 eV, which can be applied with the gap voltage of 400 V if synchronous phase of 20° is chosen. This system is considered to be attainable by an untuned re-entrant cavity.

In order to supply the beam current of 10 nA with the repetition rate of 0.5 Hz, the number of protons accelerated in a cycle is $1.3 \times 10^{11}$ if 90 % of beam extraction efficiency is assumed. If the acceleration efficiency is assumed to be 90 %, then $1.5 \times 10^{11}$ protons are required to be injected in a cycle. If we apply multi-turn injection which results in an intensity increase as large as 10 times, required peak current for the injector linac is 3 mA, which is considered well attainable by our injector linac. The space charge limit in the ring can be evaluated by the Laslett's formula as[10]

$$N = \nu \Delta\nu B \pi (a+b) b \beta^2 \gamma^3 / R r_0 ,$$

where R is the mean radius of the ring, β and γ are relativistic factors and $r_0$ is the classical radius of proton and a and b are long and short half axis of the beam ellipse and B is the bunching factor. If $1.5 \times 10^{11}$ protons are accumulated in the ring, the tune shift due to space charge repulsion is estimated to be 0.185, where a and b are estimated to be 22 and 6 mm, respectively considering the emittance dilution in the horizontal direction due to multiturn injection. The value of

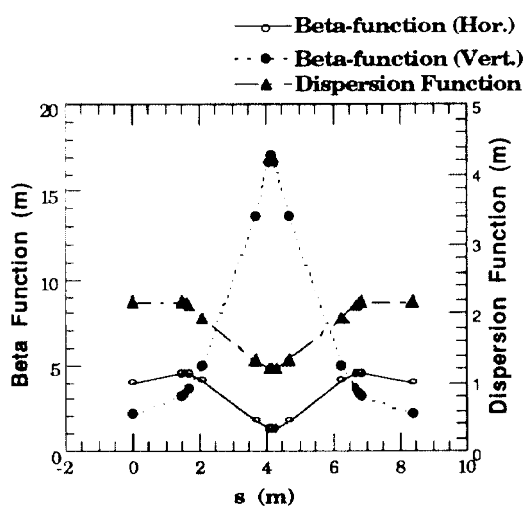

Fig. 3 Beta and Dispersion Functions of the Ring.

Table 1 Parameters of the Proton Synchrotron

| | |
|---|---|
| Injection Energy | 7 MeV |
| Extraction Energy | 70 ~ 250 MeV |
| Repetition Rate | 0.5 Hz |
| Circumference | 33.523 m |
| Focusing Structure | FBDBFO |
| Length of Long Straight Section | 3.0 m |
| Betatron Tune | |
| Horizontal | 1.75 |
| Vertical | 1.25 |
| Transition Energy | 765 MeV |
| Bending Magnet (Normal Entrance) | |
| Radius of Curvature | 2.025 m |
| Length along the Orbit | 1.591 m |
| Bending Angle | 45 Deg. |
| Field Strength | |
| Maximum (370 MeV) | 1.5 T |
| (250 MeV) | 1.2 T |
| Injection ( 7 MeV) | 0.19 T |
| Quadrupole Magnet | |
| Length | 0.20 m |
| Max. Field Gradient | |
| (QF) | 2.52 T/m |
| (QD) | 5.85 T/m |
| RF acceleration System | |
| Frequency Range | 1.087 ~ 5.491 MHz |
| Cavity | Untuned Re-entrant Cavity |
| Energy Gain Per Turn | 137 eV |
| Peak RF Voltage | 400 eV |
| Acceleration Time | 0.5 sec. |
| Scheme of Extraction | 1/3 Resonance with Transverse RF Field |
| Beam Spill Time | 0.95 ~ several hundreds sec. |
| Beam Intensity | $> 1.2 \times 10^{11}$ |

tune shift as large as 0.185 might be a little bit ambitious. This is one of the items to be tested experimentally. Our injector has relatively higher energy than other medical synchrotron. But space charge effect is to be studied if the repetition rate is not so high even if the required current is 10 nA.

## 3. POSSIBLE R&D AT THE RING

For realization of point like irradiation, it is necessary to provide sharp and monochromatic energy beam. In this case the beam should be scanned in transverse directions by, for example, Raster scans. The depth of the irradiation is controlled by changing the beam energy. For transverse scan, the extracted beam is required to be continuous in order to attain uniform dose distribution. As the method for beam extraction for proton therapy, a foil extraction of $H^-$beam was proposed by R. L. Martin[11]. However the dipole field of the ring is designed as low as 5.6 kG and the ring becomes somewhat larger.

During the slow beam extraction process, the circulating beam in the ring with larger betatron amplitude is extracted more rapidly. So as to extract the beam successively, it is needed to drive the yet stable beam to unstable condition. In the ordinary scheme, the tune is shifted to the resonance by changing the field gradients of quadrupole magnet. Ultra slow extraction invented by Dr. W. Hardt utilizes finite chromaticity and realizes overapping condition of separatrices for various momentum particles[12]. The merits of Hardt's method is the angle of the extracted beam does not change during the extraction process as shown in Fig. 4(b) while the ordinary method results in the angular deviation as the extraction proceeds (Fig. 4(a)). However Hardt's scheme requires conditions on chromatisity and phase difference between resonance exciter and the first septum, and in general, it is difficult to be included in a compact ring for proton therapy. A method of slow beam extraction with applying transverse RF field which resonates with the betatron oscillation is proposed[13] and is experimentally tested at TARN II at Institute for Nuclear Study, University of Tokyo[14]. This idea is also studied independently by Dr. K Hiramoto utilizing RF field with random phase[15]. The method utilizing transverse RF field increases the emittance of the circulating beam in the ring keeping the separatrix size fixed. So the direction of the extracted beam does not change throughout the whole extraction process at least in principle as shown in Fig. 4(c). In fact in preliminary test at TARN II, it is observed that extracted beam emittance is reduced compared with the ordinary method[14]. The extracted beam emittance by this method is expected as small as the case of Hardt's method. In addition, merit of this method is that it only needs an electrode for transverse RF field which is usually installed to measure the betatron tune value. The sextupole field is necessary only for resonance exciter and is also very simple. Only one sextupole magnet is used for the case of TARN II[16]. On and off of the extracted beam can be controlled in a few hundreds µsec by switching the RF power amplifier with some tens watts, which is suitable for synchronization with breazing in case of medical application. By this method, it is already experimentally shown that the extracted beam spill can be made as long as several hundreds seconds[14]. So if we can inject much more beam into the ring, then repetition rate of the synchrotron can be lowered and extracted beam like DC beam can be obtained. This is the reason why we make enphasis on study of space charge effect. This long beam spill time is considered to be useful also for other applications at ICR.

Another items to be studied in the ring is to make the beam transport line of the extracted beam with the same magnets as ring dipole and quadrupole magnets. As mentioned above, the largest merit of the synchrotron for proton therapy is the variability of its energy. However if the transport system is left with DC excitation mode, this merit is largely reduced. In the ring we want to investigate the possiblity of changing the beam energy from pulse to pulse and irradiate such beam with series excited transport line with the ring magnets. This idea was proposed for heavy ion synchrotron (NUMATRON)) almost ten years ago[17], however we have not yet tested it. In order to utilize this beam delivery system to medical treatment, only one beam course is available. So the patient is required to be precisely positioned beforehand in the next room radiation protected and then shifted to the exact position for treatment.

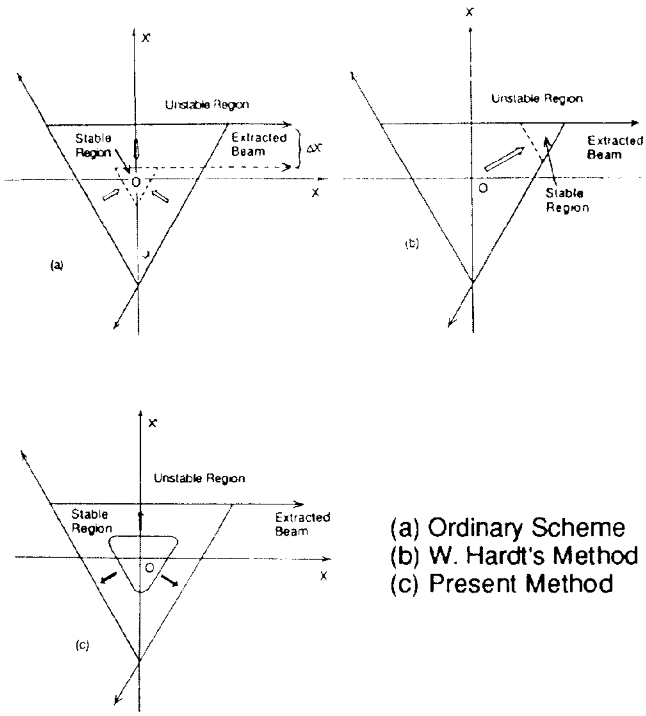


Fig. 4 Illustration of various slow extraction scheme.

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