REVIEW OF HADRON MACHINES FOR CANCER THERAPY

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Abstract

Particle cancer therapies with proton and light ion have been considered as excellent treatment for deep-seated tumors, which are due to excellent dose distributions with Bragg peak. To realize these therapies, dedicated accelerator facilities were constructed. With good clinical results in these frontiers, many plans of dedicated facility have been started in the both case of proton and light ion treatment facilities. In this paper, important types of accelerator facilities will be presented.

INTRODUCTION

Though radiotherapy of cancer patient is important treatment method, X-ray will be mainly used. This situation is from the low cost and compactness of the required hardware. If we can use charged particle beam like proton and light ion for deep seated tumor, depth dose distribution can be improved to concentrate the dose. This advantage is pointed out first by R.R Willson[1] in 1946. This comes from the existence of Bragg peak in the case of charged particle beam. We can adjust the depth position of Bragg peak at tumor to obtain high concentration of the particle dose.

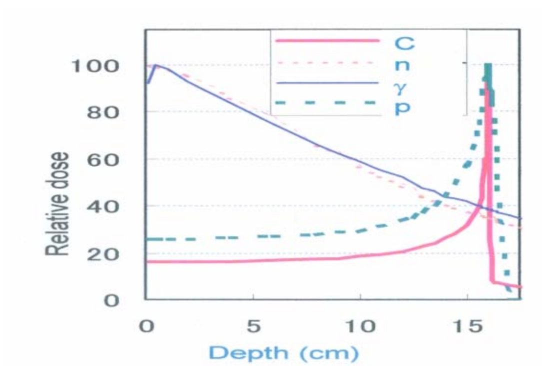

Figure 1: Depth dose distribution of X-ray, neutron, proton, and carbon ion.

In the actual treatment with charged particle, Bragg peak with different energies must be superimposed to fit on the tumor thickness. In Fig.2, calculated depth dose distributions[2] of several ions are compared with a SOBP (Spread Out Bragg Peak) width of 6cm. In these calculations, nuclear interactions of the incident beam with water and RBE (Relative Biological Effectiveness) are included. As seen from these calculations, entrance dose is less than 70% of the dose value at SOBP, which make the entrance dose on normal tissue low. In the cases of X-ray and neutron, the dose values are decrease gradually in the patient body, and this nature is demerit in the treatment of a deep seated tumor.

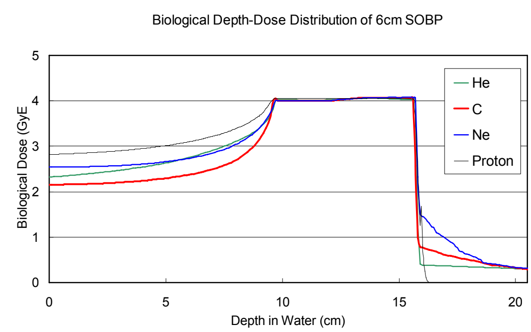

Figure 2: Calculated depth dose distributions of proton, helium, carbon, and neon beams with SOBP of 6xm.

In the case of light ion, there is another merit concerning biological effect. If we see the RBE as a function of a LET (Linear Energy Transfer), the RBE is maximum around 200keV/μ as shown in Fig.3. In the case of carbon, the RBE value at entrance is low with small LET value, and the value at SOBP region is high. This makes desired characteristic point that kill tumor effectively with light side effect on the normal tissue. With low OER (Oxygen Enhancement Ratio), carbon beam can well control the tumor of hypoxic cell that is considered as radio-resistant.

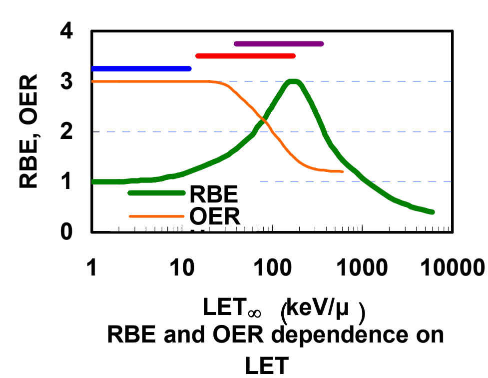

Figure 3: RBE and OER as a function of LET.

NEW IDEAS OF THE ACCELERATORS FOR RADIO-THERAPIES

Though there are already dedicated accelerators for cancer therapy that are used for routine treatments, several new ideas are presented. One is proposed by U. Amaldi[3], and is shown in Fig.4. In this system, beam is accelerated with cyclotron at the first stage, and is accelerated with linac up-to a required energy for therapy. To compact the linac, high frequency as 3 GHz is used, beam test was performed with one unit of this linac system. To verify the system as a dedicated accelerator for cancer treatment, further R&D is left.

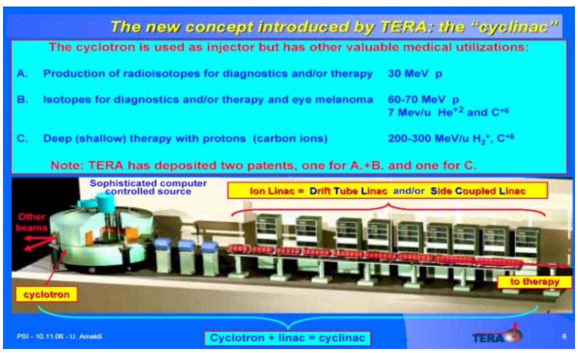

Figure 4: Accelerator concept of LIBO (Linac Booster).

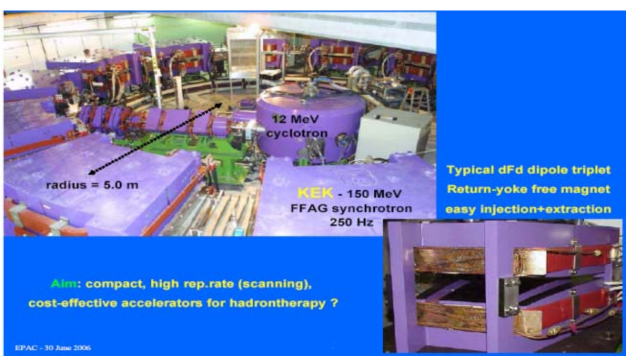

Figure 5: FFAG at KEK.

New type of accelerator is proposed by Mori et al[4], which is FFAG (Fixed Field Alternating Gradient synchrotron). They constructed a proton machine which has maximum design energy of 150 MeV. Though they could demonstrate the beam acceleration up-to 100 MeV, the size is larger than the dedicated synchrotron for proton therapy.

There is design study of super-conducting cyclotron for light ion radio-therapy by L.Calabretta et. al.[5]. In their design study, diameter of the cyclotron is as small as 5m. To realize the cyclotron that is used for cancer therapy, R&D is required.

PROTON FACILITIES

A dedicated proton facility (see Fig.6) with gantries was constructed at Loma Linda University (USA), and the treatment was started in 1990. A main accelerator is synchrotron, and there are three gantries and one horizontal fixed line. This is first hospital-based facility, and accumulated patient number was 10324 at July 2005. Another choice of accelerator is cyclotron. In Fig.7, normal-conducting cyclotron at NCC (Kashiwa, Japan) is shown that was constructed by IBA and Sumitomo. Accelerated beam energy is fixed, and required beam energy for therapy is obtained by use of a degrader. At PSI, super-conducting cyclotron was installed as shown in Fig.8, which was manufactured by ACCEL. In this facility, spot-scanning irradiation was adopted.

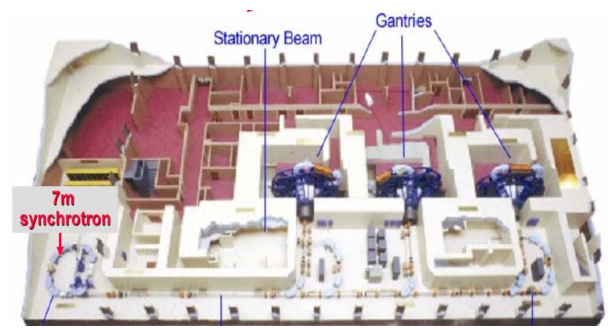

Figure 6: Lay-out of the proton facility at Loma Linda University.

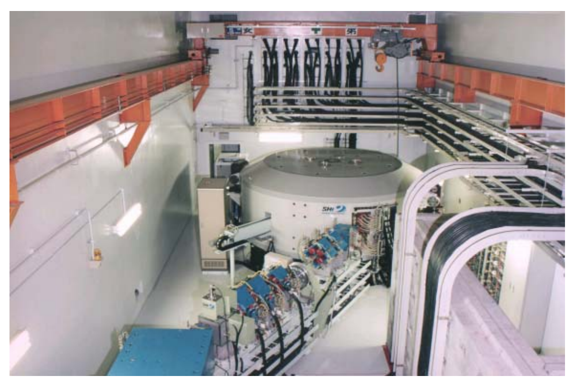

Figure 7: Normal conducting proton cyclotron by IBA at Kshiwa.

Figure 8: Super conducting cyclotron by ACCEL at PSI.

LIGHT ION FACILITIES

Firstly, ion beam was used for cancer therapy at LBNL (Lawrence Berkeley National Laboratory, USA) by use of the Bevalac, which was constructed for physical experiments. Following the pioneering works at LBNL in this field, a dedicated facility of HIMAC (Heavy Ion Medical Accelerator in Chiba) was constructed at NIRS (National Institute for Radiological Sciences; see Fig.9). The maximum beam energy is 800MeV/u in the case of e/m=0.5, and required ion species are from He to Ar. There are three treatment rooms. In one room, there are horizontal and vertical beam lines. In other rooms, we can use only horizontal or vertical beam line. Treatment was started in June 1994 with carbon beam, and more than 3000 patients have been treated until December 2006. In the clinical study, fractionations were reduced in the cases of lung and liver tumors, and now treatments with one and two fractions are practiced with better tumor controls, respectively. In the case of radio-resistive tumor like a bone and soft tissue sarcomas, good clinical results are obtained also. Following HIMAC, a dedicated facility was constructed at Hyogo in Japan, where proton beam can be used also. The gantry was equipped in the proton room as shown in Fig.10.

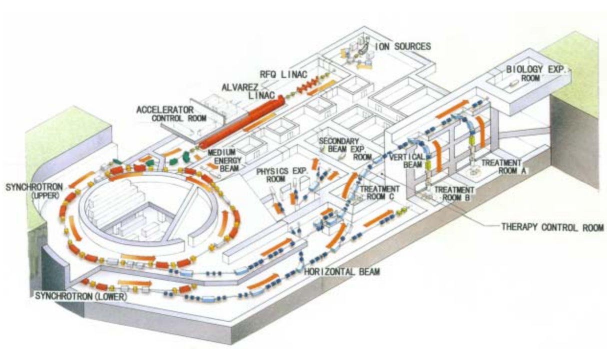

Figure 9: HIMAC facility.

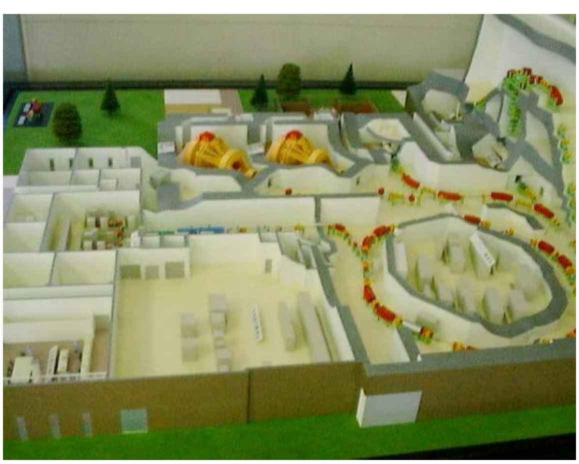

Figure 10: HIBMC at Hyogo.

At GSI (Gesellshaft fur Schwerionenforschung), treatment with carbon beam from a synchrotron of SIS18 was started in 1997. In this treatment, irradiation with raster scanning was developed, where beam energy is changed in the synchrotron during the irradiation. With this irradiation method, 198 patients have been treated successfully until December 2003. Based on the experiences with carbon ion radio-therapy, construction of a dedicated facility of HIT(Heidlberger Ionenstrahlen-Therapie; see Fig.11) was built at Heidelberg[6]. In this facility, there is one gantry room that is first one in the ion beam facility. In this facility, proton beam is also expected to use for therapy.

In Italy, there is a project of CNAO (Centro Nazionale di Adroterapia Oncologica) [7], which is under construction in Pave. Though the injector linac is expected to use same one as in HIT, there is no gantry in this facility as shown in Fig.12.

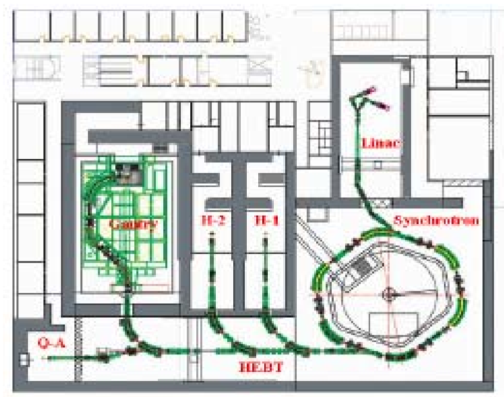

Figure 11: Layout of HIT (Heidlberger Ionenstrahlen-Therapie) at Heidelberg.

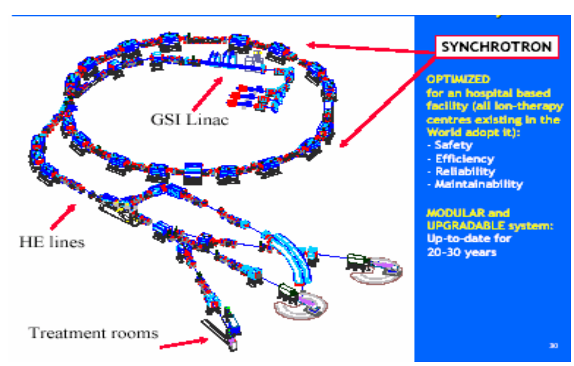

Figure 12: CNAO at Pave (Italy).

At Lanzhou in China, there is a plan to use carbon beam for cancer therapy of a deeply seated tumor at IMP (Institute of Modern Physics) with a newly constructed CSRm synchrotron that is shown in Fig.13. As a first step of this plan, superficially-placed tumors were treated last year[8] with carbon beam of 100 MeV/u that was accelerated in a cyclotron of SSC.

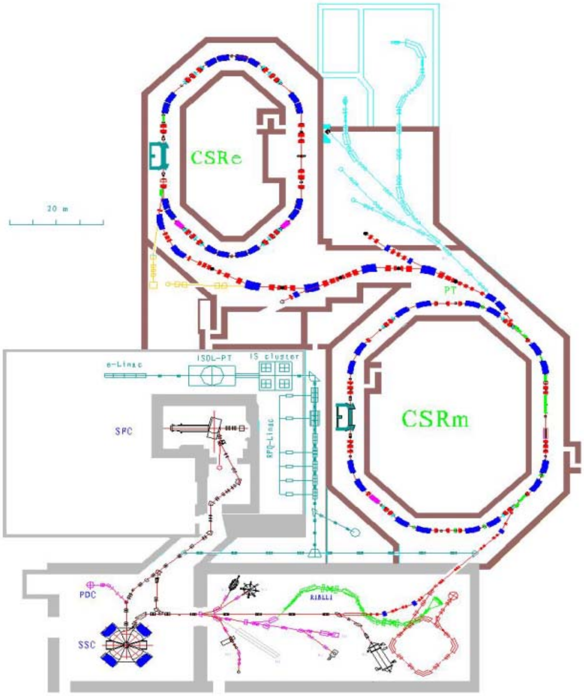

Figure 13: Accelerator facility at IMP.

At NIRS in Japan, design of a compact facility with carbon ion beam was performed, which must have good stability and reliability. These properties are important in the dedicated radio-therapy facility to treat many patients. The designed facility[9] consists of an ECR ion source with permanent magnet, an RFQ linac, an APF-IH linac with 4 MeV/u, and a synchrotron with maximum energy of 400 MeV/u. There are three treatment rooms. One is equipped with horizontal and vertical ports, and other two are equipped with horizontal or vertical port as seen in Fig.14. Concerning the important subsystem in this new design, beam tests of linacs, an acceleration cavity in the synchrotron, power supply for lattice quadropole magnet, and new irradiation devices have been performed. A tested injector system is shown in Fig.15, and the accelerated beam intensity was 490 eμA with fully stripped carbon beam. This beam intensity is twice the required value in the system design[10]. Based on these tested results of each component, the dedicated facility will be realized at Gunma University in 2009.

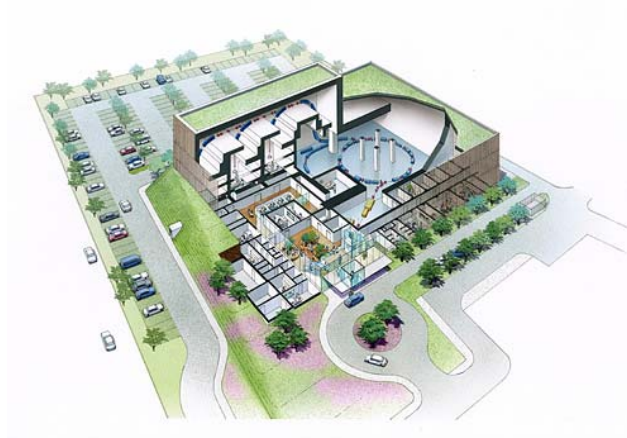

Figure 14: Image of the designed facility for Gunma University.

Figure 15: Tested injector system with an APF-IH linac.

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