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Physical design of a single-amplifier-driven proton linac injector for a synchrotron-based proton-therapy system in China

P.F. Ma [a,b,c], S.X. Zheng [a,b,c], X.D. Yu [a,b,c], Y. Lei [a,b,c], R. Tang [a,b,c], Q.Z. Xing [a,b,c,*], X.L. Guan [a,b,c], X.W. Wang [a,b,c], C.P. Wang [d], J. Qiao [d], X.C. Xie [d], F. Yang [d], Y.H. Pu [d]

[a] *Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China*
[b] *Laboratory for Advanced Radiation Sources and Application, Tsinghua University, Beijing 100084, China*
[c] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[d] *Shanghai APACTRON Particle Equipment Company limited, Shanghai 201800, China*

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ABSTRACT

This paper describes the physical design of a 7 MeV proton linac injector for a synchrotron-based proton-therapy system, sponsored by the Chinese government under the support of the National Key Research and Development Program. The proton linac injector consists of an electron cyclotron resonance proton source, a low-energy beam transport section, a radio-frequency quadrupole (RFQ) accelerator, and an Alvarez-type drift tube linac (DTL). The peak current of the proton beam at the exit of the DTL accelerator is required to exceed 12 mA, with a normalized emittance of $\leqslant 1.2\pi$ mm mrad (90% particles), a repetition rate of 0.5 Hz, and a beam pulse width of 40–100 μs. For the beam current whose momentum spread falls within ±0.3%, the intensity must exceed 8 mA. The design of the linac injector is optimized in the principle of adopting sophisticated domestic technologies and cost control. Only one tetrode-based RF power amplifier is required after minimizing the total peak-power consumption of the RFQ and DTL accelerator, which is 378 kW. The idea of the RF power lines feeding two cavities with one amplifier is presented. To facilitate the manufacture of permanent-magnet quadrupoles and reduce the cost, the focusing strength at the end of the RFQ accelerator is optimized. Consequently, the focusing strength of all permanent-magnet quadrupoles is the same, and the DTL accelerator can be directly connected to match the RFQ accelerator without a medium-energy beam transport section between them. After construction, the 7 MeV proton linac injector is hoped to be the first homemade linac injector for a synchrotron-based proton-therapy facility in China.

1. Introduction

Proton therapy is a type of particle therapy technique utilizing proton beams for cancer treatment. Due to its biological nature, radiation can prevent the division and rapid growth of cancer cells, thereby destroying most cancer tissues or causing them to wither [1].

Proton therapy has obvious advantages over the traditional radiation therapy that utilizes photon beams [2]. The energy deposition of a photon beam decays gradually with the incident depth after it reaches the maximum. Meanwhile, the energy deposition of a proton beam reaches the maximum value near the range of the beam, i.e., the Bragg peak. In addition, the energy loss on the path of the proton away from the Bragg peak is low. With the energy modulation of the proton beam, the tumor can be covered by Bragg peaks [3]. In fact, proton therapy delivers lower energy deposition in healthy tissues than photon beam therapy.

According to data from the Particle Therapy Co-Operative Group [4], the number of patients treated by proton-therapy facilities and the number of such facilities in operation have increased (Fig. 1).

High-energy protons for the proton-therapy system are produced by accelerators. The two popular alternatives to proton accelerators are cyclotrons and synchrotrons [5]. Only two proton-therapy facilities in operation operate in mainland China, namely, WPTC/Zibo (cyclotron based) and SPHIC/Shanghai (synchrotron based) [4]. Several proton-therapy facilities are under construction or in the planning stage. The main advantage of synchrotrons is that relatively less radiation doses are produced when adjusting the output beam energy. The proton linac injector is an important factor with respect to the operating performance

* Correspondence to: Room 309, Liuqing Building, Engineering Physics, Tsinghua University, Beijing, 100084, China.
E-mail address: xqz@tsinghua.edu.cn (Q.Z. Xing).

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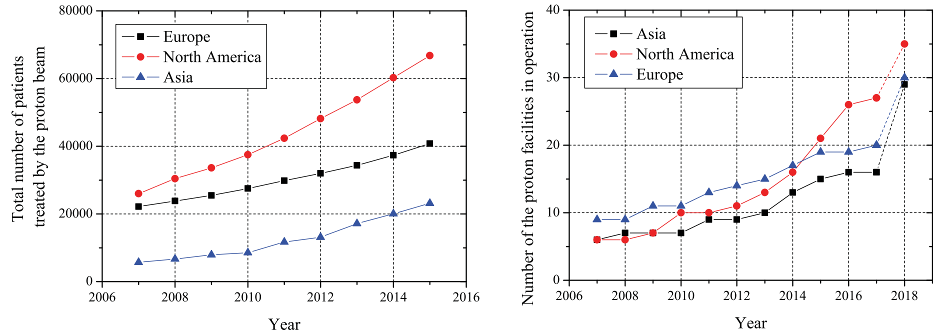

Fig. 1. Number of patients treated by proton beam (left) and number of proton facilities in operation (right) in Asia, North America, and Europe.

Table 1
Beam requirements at the exit of the linac injector for the synchrotron-based proton-therapy system.

Parameter	Value
Ion type	Proton
Output beam energy	7 MeV
Output beam momentum spread	±0.3% (⩾8 mA)
Output peak current	⩾12 mA
Output normalized transverse emittance (90% particles)	⩽1.2π mm mrad
RF frequency	325 MHz
Repetition rate	0.5 Hz
Output beam pulse width	40–100 μs

and manufacturing cost of synchrotron-based therapy systems. To promote localization, the construction of a proton linac injector for a synchrotron by the Shanghai APACTRON Particle Equipment Company Limited has been approved by the Chinese government. This homemade proton linac injector for a synchrotron-based proton-therapy system is hoped to be the first in China. The linac injector is required to accelerate proton beams to 7 MeV for injection into the synchrotron. The requirements of beam parameters at the exit of the linac injector are listed in Table 1.

In the low-energy section of the linac injector, the radio-frequency quadrupole (RFQ) accelerator is usually adopted instead of the large Cockcroft–Walton DC pre-accelerator [6]. A combined zero-degree structure or alternating phase focusing interdigital H-type drift tube linac (DTL) can be an alternative approach to forming the high-energy section of the linac injector [7,8]. A compact linear accelerator as proposed by the AccSys Company (CA, USA) for the market [9] is preferred. Furthermore, A.D. Kovalenko [10] proposed a compact proton injector for synchrotrons, and this injector comprises a conventional four-vane RFQ structure and an RFQ with spatial periodic RF quadrupole focusing.

For the domestic proton linac injector in Shanghai, design optimization is carried out in the principle of adopting sophisticated domestic technologies and cost control. The radio-frequency (RF) power source accounts for a large proportion of the construction cost of the entire injector. Thus, the design of the RFQ and DTL accelerator is improved so that only one tetrode-based RF power amplifier is sufficient to provide RF power to the cavities of the RFQ and DTL. One Alvarez-type DTL with samarium–cobalt permanent magnets as the transverse focusing quadrupoles, which has been applied to SNS [11], J-PARC [12] and Linac4 [13], is exploited to accelerate the proton beam to 7 MeV. This type of DTL has been applied to two projects (CPHS/Beijing [14] and XiPAF/Xi'an [15]) in China. With the drift tube suspended in the RF cavity, a periodic focusing magnetic field is provided by the permanent-magnet quadrupoles (PMQs) mounted inside the drift tubes to maintain the transverse stability of the proton beam [16]. The focus strength of all PMQs is the same, and the DTL accelerator can be directly connected to match the RFQ accelerator without a medium-energy beam transport (MEBT) section between them. The four-vane-type is selected for the RFQ accelerator due to its good structural stability and substantial manufacturing experience in China. The well-developed electron cyclotron resonance (ECR) source [17] is chosen as the proton source.

To present the physical design of the 7 MeV proton linac injector for proton-therapy system, this paper is organized as follows. Section 2 describes the optimization process of the proton linac injector, Section 3 presents the design results and error analysis, and Section 4 is the conclusion.

2. Optimization process

2.1. Overall configuration

The proton linac injector consists of an ECR proton source, a low-energy beam transport (LEBT) section, an RFQ accelerator, and an Alvarez-type DTL accelerator. One-tetrode-based RF power amplifier is required to provide the RF power for the RFQ and DTL cavities. The schematic of the linac injector is presented in Fig. 2.

2.2. One-tetrode-based design of RFQ & DTL

Compared with other typical power sources such as the klystron, IOT, solid-state amplifier, the tetrode is considered to be the cheapest solution to providing RF power at 352 MHz with a peak power of 350 kW and duty factor of 4.9% for spoke cavities at ESS and FREIA [18]. For the proton linac injector, the cost can be reduced if only one tetrode is used. From the latest result of the high-power test on the tetrode-based RF power amplifier for the XiPAF project in China, the amplifier has successfully produced RF power at 325 MHz with a peak power up to 500 kW, a repetition rate of 1 Hz, and a pulse width of 150 μs [19]. Consequently, 500 kW is estimated to be the upper limit for the output peak power of the amplifier, with a duty factor of 1.5×10^{-4}. Considering an RF loss budget of 10% and a control margin of 15%, the power consumed inside the cavities of the RFQ and DTL is required to be ⩽395 kW. RF power can be transmitted partly to the RFQ and partly to the DTL after passing through a power divider. Power assignment and phase matching are the key issues that should be discussed after the physical design. The primary idea of the power line is shown in Fig. 3.

2.2.1. DTL

Apart from the power source, the capital cost of the linac injector is also affected by the length of the linac. Obviously, the total length of the linac can be reduced by shortening the length of the conventional low-acceleration-gradient RFQ [20]. Thus, the transfer energy between the RFQ and DTL accelerator is limited by the minimal injection energy into the DTL, which is determined by the first cell of the DTL. The length of the first cell of the Alvarez DTL, $\beta\lambda$, is required to be larger than $L_1 + 2L_2 + L_3$, where β is the relativistic velocity of the incident particles, λ is the resonant wavelength in free space (λ is equal to 0.923 m for the RF frequency of 325 MHz), L_1 = 40 mm is the length of the PMQs, L_2 = 10 mm is the wall thickness of the drift tubes, and L_3 is