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A lattice scenario for a proton radiography accelerator

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Abstract A proton radiography system is an accelerator-based facility. Especially high-energy proton radiography is an advanced hydrodynamics diagnostic tool, and it is the trend of radiography technology development. In this paper, a 20 GeV accelerator complex scenario, including a 35 MeV linac, a 1 GeV booster and a 20 GeV main ring, is introduced. The overall physics design of the proton radiography accelerator is described, including the design of each part of the accelerator and the choice of the main parameters.

Key words proton radiography, accelerator, lattice

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1 Introduction

X-ray radiography is a well-known diagnostic tool for nondestructive testing, of both static and dynamic systems. Pulsed X-radiography is commonly used for the study of a number of physical problems involving the hydrodynamics of materials, such as the stability of accelerated material interfaces and the response of targets to ballistic penetration. X-ray sources have been used for the past 30 years to study hydrodynamic phenomena. However, the development of X-radiography is getting harder for the limitation of dose and spot size, which is caused by the physics of electron and gamma ray interactions with matter.

Recently, high-energy proton radiography [1] was recognized to be a new tool that is far superior to flash X-radiography. High energy proton beams have a mean free path that is much better matched to diagnose hydrodynamic systems than X-rays. What's

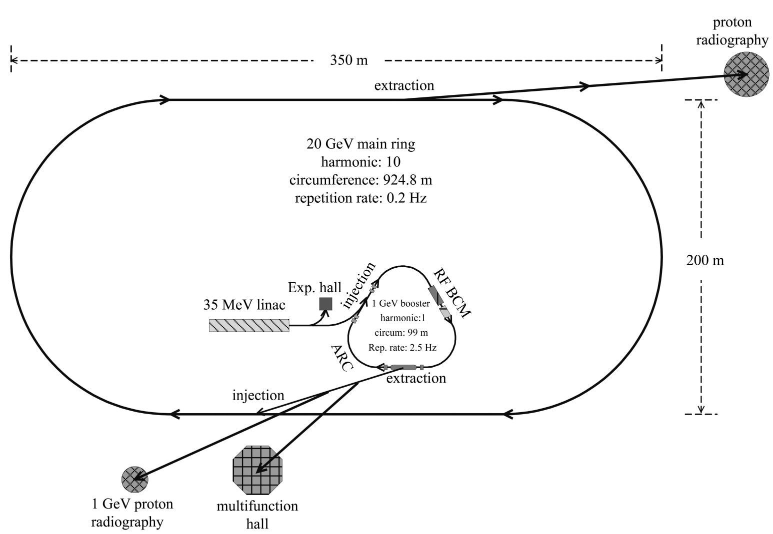

Fig. 1. Layout of the proton radiography facility.

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more, a pulsed proton radiography system is capable of obtaining multi-axis, multi-pulse data in a single dynamic test and producing a high-resolution radiography movie of a dynamic test object.

To acquire proton radiographic images with high spatial and temporal resolution, the desired beam pulse structure should be flexible, with 10^{11} to 10^{12} protons in a 20–30 nanosecond long pulse per view, and a variable time separation between pulses from 100 nanoseconds to many microseconds. Fig. 1 shows a conceptual design layout for a facility that can meet the above requirements, including the linac, the booster, the synchrotron and the beamlines.

2 Linac

A 35 MeV proton linac [2] is presented by the Institute of High Energy Physics (IHEP) and the current study is based on use of the drift tube linac (DTL) cavities from that. To improve the beam quality, we decided to rebuild the forepart of the linac. A new ion source and radio-frequency quadrupole linac (RFQ) are under construction. Fig. 2 shows the sketch map of the linac.

Fig. 2. Sketch map of the 35 MeV linac. IS: Ion Source; LEBT: Low Energy Beam Transport; MEBT: Medium Energy Beam Transport.

The new Electron Cycling Resonance (ECR) ion source is 0.6 m long, which can provide a proton beam with 50 mA peak current, 50 keV kinetic energy and 0.2 πmm·mrad normalized emittance (rms). A new four-pole type RFQ cavity is adopted, with a total length of 1.3 m. The RFQ accelerates the proton beam from 50 keV to 0.75 MeV, with a duty factor of 0.2%. The choice of 0.75 MeV output energy matches the injection energy of the DTL. At the end of the RFQ, the beam's transverse normalized emittance is 0.2 πmm·mrad and the momentum deviation is ±1%. The DTL accelerates the 0.75 MeV beam from the RFQ to 35 MeV. Through stable operation for more than twenty years in the Beijing Proton Linac, they are proved to be capable.

This upgrade can improve the beam's transverse normalized emittance from 6 πmm·mrad to 1 πmm·mrad (rms) and the momentum deviation from ±0.6% to ±0.3%. Such a linac acts not only as an injector but also as a facility for nuclear experiment research.

3 Booster

The lattice lays emphasis on the synchrotron. A 3-fold symmetric lattice is chosen to separate the injection, the RF acceleration and the extraction to different straights. Fig. 3 shows the structure and the twiss parameters of one super-period. The whole lattice adopts a triplet structure, and contains 12 dipoles and 27 quadrupoles. The detailed beta functions and dispersions are shown in Table 1. Each straight section consists of one 8 m long dispersion-free drift space. Such an uninterrupted long straight section is good to accommodate the injection and extraction devices.

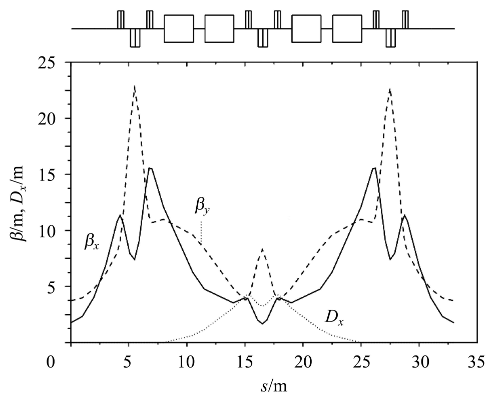

Fig. 3. The structure and twiss parameters of the booster in one super-period.

The injection course is carried out within four turns. At the end of the injection, the beam is nearly an unbunched beam. The acceleration is performed by one ferrite-loaded cavity which provides 20 kV RF voltage with a harmonic number of one. The waveform of the RF voltage is optimized to increase the bunching factor during the accelerating course. The maximum synchronous phase is about 10 degrees and the maximum tune shift is limited within 0.1, which is acceptable for the booster.

With an injection energy of 35 MeV and 1.2×10^{12} protons in the ring, a minimum 95% emittance of 60 πmm·mrad is required. For calculating the magnet apertures, we use the transverse acceptance of 100 πmm·mrad. It should be kept in mind that, with the low repetition rate, fairly high beam losses are tolerable. So the beam collimator can be ignored in the ring.

At the end of acceleration, the beam width is 125 ns and the maximum momentum deviation is ±0.4%. The transverse 95% emittance is about 20 πmm·mrad.

Table 1. Parameters of the booster.

parameters	values
injection energy/MeV	35
extraction energy/GeV	1
repetition rate/Hz	2.5
circumference/m	99
harmonic No	1
particles per pulse	1.2×10^{12}
$\text{tunes}_{(x,y)}$	3.3, 2.28
uncorrected chromaticity $_{(x,y)}$	−3.7, −4.5
maximum tune $\text{shift}_{(x,y)}$	0.06, 0.08
transition factor	3.7
transverse acceptance/(πmm·mrad)	100
maximum RF voltage/kV	20
RF frequency/MHz	0.8–2.6
max beta $\text{functions}_{(x,y)}$/m	15.6, 22.7
max dispersion/m	4.3
dipole length/m	2.5
dipole B/T	0.18–1.2

Power supply sets of magnet: 1 for dipoles and 3 for quadrupoles.

4 Main ring

We are proposing a lattice for the synchrotron with a transition gamma of about 18 i. A lattice with imaginary transition energy avoids transition and stays away from some instabilities. Fig. 4 gives the lattice structure and twiss parameters for the whole ring. Fig. 5 shows the lattice functions for one arc cell. The detailed parameters are shown in Table 2. A useful feature of this particular lattice is that the maximum of the horizontal beta function is located near a zero of the dispersion. This reduces the apertures required. With a full-aperture emittance of 30 πmm·mrad, Figs. 3 and 4 show that magnets with full apertures of 10 cm should be sufficient.

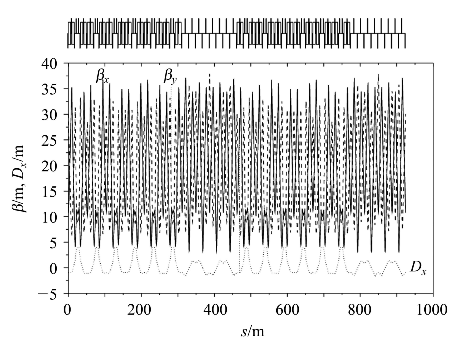

Fig. 4. The structure and twiss parameters of the main ring.

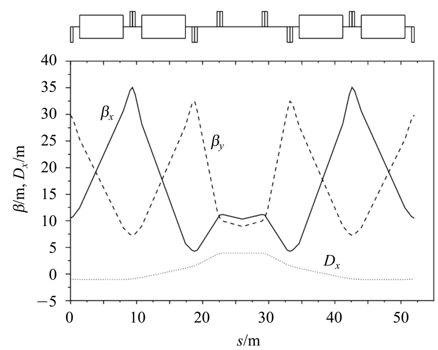

Fig. 5. The lattice structure and twiss parameters for one arc cell.

Table 2. Parameters of the 20 GeV main ring.

parameters	values
injection energy/GeV	1
extraction energy/GeV	20
repetition rate/Hz	0.2
circumference/m	924.8
harmonic No	10
particles per pulse	1.2×10^{13}
$\text{tunes}_{(x,y)}$	12.76, 10.73
uncorrected $\text{chromaticity}_{(x,y)}$	−15.9, −15.2
maximum tune $\text{shift}_{(x,y)}$	0.11, 0.13
transition factor	18 i
transverse acceptance/(πmm·mrad)	30
maximum RF voltage/kV	100
RF frequency/MHz	2.8–3.3
max beta $\text{functions}_{(x,y)}$/m	37.1, 37.9
max dispersion/m	4.0
dipole length/m	6.6
dipole B/T	0.11–1.4

There are two straight sections in the main ring. Each of them consists of eight FODO cells, and the dispersion functions are no more than 1.5 m. The long drift of almost 8.6 m long between an F and a D quadrupole is available for the kicker. The injected beam size is about 5 cm in diameter at the kicker, and it shrinks during the acceleration to about 2 cm. When the beam extraction happens, the beam width is about 20 ns and the maximum momentum deviation is about ±0.16%.

5 Summary

The above accelerator scenario is suitable for proton radiography. In addition, such a scenario can be upgraded to more views and more particles for a better differentiation rate.

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