Full period superconducting section physics design for injector Ⅱ of China-ADS *

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Abstract: The China Accelerator Driven Subcritical System (China-ADS) project, which is a strategic plan and aims to design and build an ADS demonstration facility, has been proposed and launched actively in China. Injector Ⅱ as one of the parallel injectors of China-ADS, and is prompted by the Institute of Modern Physics (IMP). In this paper, a new scheme with full period lattice structure for the SC section is proposed. In the new scheme, there are sixteen periods, with one superconducting solenoid and one superconducting cavity included in each period. All of the elements are contained in four cryomodules. The dreadful influence of the mismatch caused by period structural change can be avoided, and the beam quality is favorable. In addition, this new scheme has certain advantages in reducing the project's difficulty and construction risk. The details of the design and beam dynamic simulation for the full period lattice structure are given in this paper.

Key words: China-ADS, Injector Ⅱ, SC section, full period lattice structure

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1 Introduction

The China Accelerator Driven Subcritical System (China-ADS) linac is a continuous wave (CW) proton accelerator, which is a strategy plan to solve the nuclear waste and resource problems for nuclear power plants in China [1]. The China-ADS linac consists of two parallel injectors: a medium energy beam transport (MEBT) and a superconducting main linac. The main proton beam parameters and beam performance for China-ADS are presented in Table 1.

Table 1. Specifications of the required proton beams.

parameters	value
particle	proton
energy/GeV	1.5
current/mA	10
beam power/MW	15
RF frequency/MHz	162.5/325/650
duty factor(%)	100
beam loss/(W/m)	$<$1
beam trips/year	$<$25000(1 s$<t<$10 s)
	$<$2500(10s$<t<$5 min)
	$<$25($t>$5 min)

In China-ADS's design, two parallel injectors are adopted in order to meet the requirements of high stability and reliability. One injector is used as the hot spare of the other. For injector scheme Ⅱ, a full period lattice structure for superconducting(SC) section is proposed to accelerate the beam out of the RFQ from 2.1 MeV to 10 MeV after being compared with several other different lattice structures. In this paper, the full period acceleration structure of SC section for injector scheme Ⅱ is demonstrated.

2 General consideration and philosophy on SC section design

The beam at the exit of the RFQ is difficult to be accelerated from lower energy to higher energy quickly and efficiently due to the intrinsic properties of the low energy beam, such as strong space charge effect and wide bunch phase width. The compensation among acceleration, bunching and focusing needs to be considered . The main parameters of the acceleration and focusing elements are set based on several factors, as follows:

(1) Zero current phase advance per cell needs to be less than 90° in order to avoid parameter resonances.

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(2) Smooth variation of the average phase advance.

(3) The beam working point should be kept away from the resonance region in the Hoffman chart.

(4) In order to avoid beam lost caused by nonlinear forces and space charge forces, the absolute value of synchronous phase that is set to be ten times root-mean square beam phase width aiming to increase the redundancy.

(5) The cavity voltage needs to be higher than the multipacting point of cavity in order to avoid the multipacting effect.

(6) At the same time, the tune depression is to be kept above 0.4, limiting the number of mismatch resonances [2].

3 Introduction of acceleration structure

A half wave resonator (HWR) is a type of mature cavity, and it has been used in several projects, such as Fermi Lab [3], ANL [4] and SARAF [5], this experience can be taken into the design and operation phases. Based on the above considerations, HWR cavities with frequency of 162.5 MHz are applied as the acceleration elements in the SC section of injector Ⅱ. Superconducting solenoids are the transverse focusing elements. The main parameters of the SC section elements are listed in Table 2. The structure of HWR cavities is shown in Fig. 1.

Table 2. Main parameters of SC section elements.

parameters	value
beta of HWR	0.10
frequency of HWR/MHz	162.5
effective length of HWR/mm	210
epeak of HWR/(MV/m)	25
bpeak of HWR/mT	60
effective length of solenoid/mm	60
maximum magnetic rigidity/(T·m)	0.41

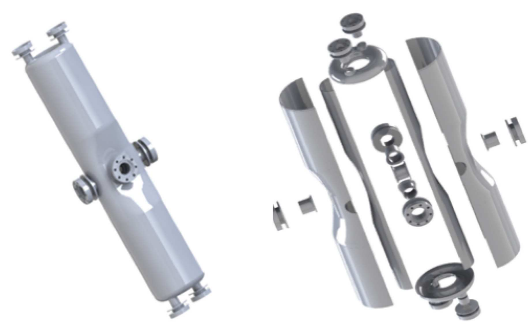

Fig. 1. The structure of HWR cavity.

In order to control the impaction caused by the strong space charge effect in low energy section, a compact and strong focusing structure is needed. For a long lattice structure, the beam quality can be influenced by several factors, especially the mismatch caused by lattice structure change. In order to avoid the mismatch effect, a full period lattice structure, which has obvious advantages in beam dynamics, is adopted in the SC section of injector Ⅱ. The lattice structure layout in one cryomodule for the SC section is presented in Fig. 2, and the whole lattice structure of the superconducting section is composed of four cryomodules with this kind of period structure, which consists of one solenoid and one HWR cavity.

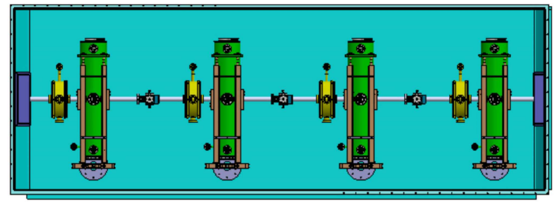

Fig. 2. The lattice structure layout in a cryomodule.

This kind of lattice structure has several advantages, not only in dynamics but also in engineering. First, the cryomodule structure is more flexible. It can accommodate one period, two periods, or even more periods without affecting the beam dynamics performance and this is convenient to the mechanical engineer. Second, it helps minimize the possibility of mismatch within one section. Third, this kind of structure avoids the mismatch caused by repeatedly matching between different cryomodules. Finally, it benefits beam commission and beam alignment.

4 Beam dynamics simulation

The beam dynamics tracking study has been carried out at 10 mA with space charge effects included. The layout of the lattice structure for the SC section is shown in Fig. 2. The SC section line is composed of sixteen HWR cavities and sixteen solenoids, which are included in four cryomodules. The effective length of each solenoid is 60 mm, and the HWR cavity installation length is 210 mm. The total length of the SC section is 18.56 m. The beam diagnostics devices are expected to be installed in the spaces between every two periods but not between two cryomodules. The beam parameters used in the beam dynamics simulation are listed in Table 3. The root-mean square (RMS) beam size in both transverse and longitudinal planes along the SC section is presented in Fig. 3.

Table 3. Parameters for beam dynamics simulation.

parameters	value
input energy/MeV	2.1
output energy/MeV	10
beam current/mA	10
ε_{xy}/(mm·mrad)	0.206
ε_z/(mm·mrad)	0.262

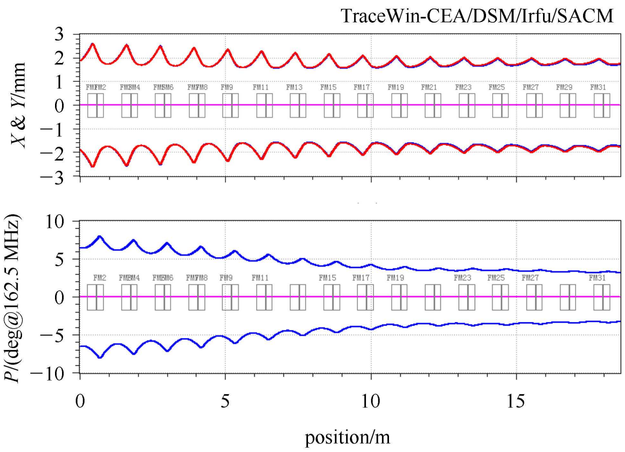

Fig. 3. The RMS beam size evolution in three planes along the SC section.

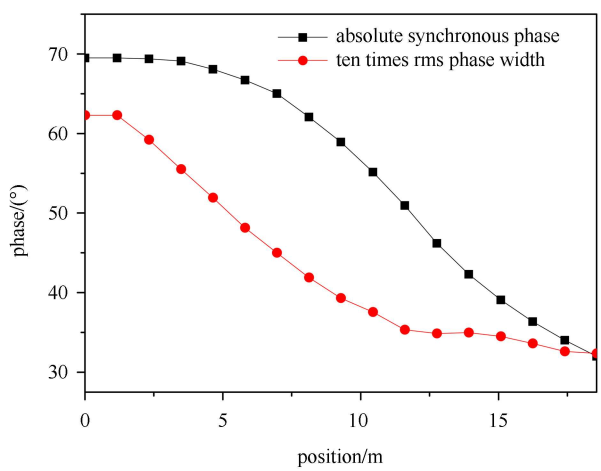

Fig. 4. The absolute synchronous phase and 10 times RMS phase width along the SC section.

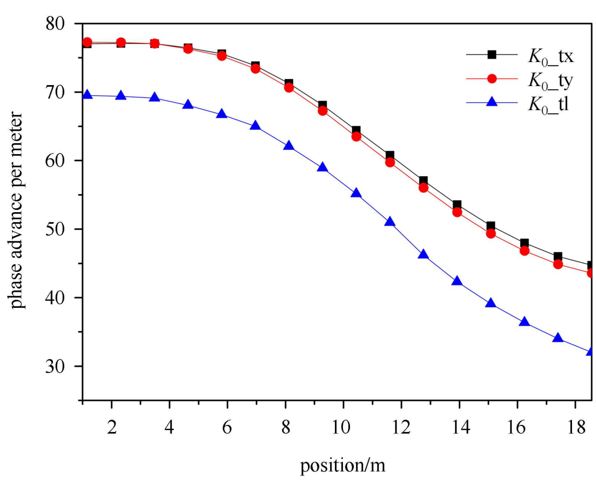

Fig. 5. The phase advance per meter along SC section.

In order to reduce beam loss and increase the redundancy, the synchronous phase need to be kept larger than 10 times the RMS phase width throughout the SC section, as shown in Fig. 4. The phase advance per meter is shown in Fig. 5 and it changes quite smoothly.

Another restriction is to keep the work points far away from the resonance region of the Hoffman chart, as shown in Fig. 6. The Hoffman stability chart is defined by initial rms emittance ratio, and the picture is plotted by k_{xy}/k_{xy0} on ordinate axis as a function of k_z/k_{xy} on abscissa axis. The chart in color code indicates the theoretically expected growth rate of emittance transfer caused by resonant action of space charge. The blank area in between the resonances indicates the absence of emittance coupling. This is described in detail in Refs. [6–9]. We can see that all of the tune footprints are in the resonance-free region in this lattice structure.

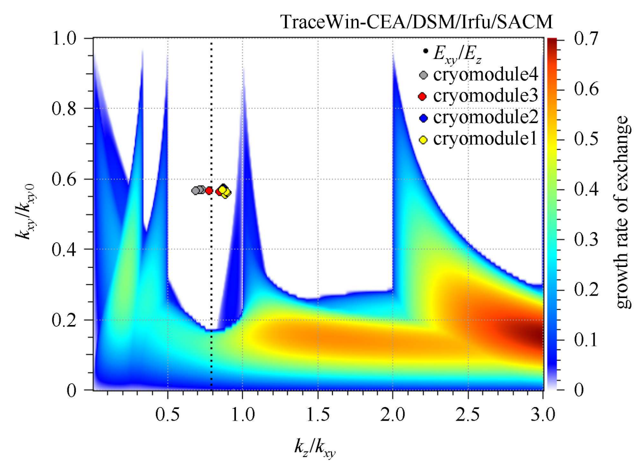

Fig. 6. Hoffman chart at SC section.

5 Multiparticle tracking results

The multi-particle tracking has been carried out for the SC section with 100000 particles based on 3σ Gaussian particle distribution. The tracking is performed

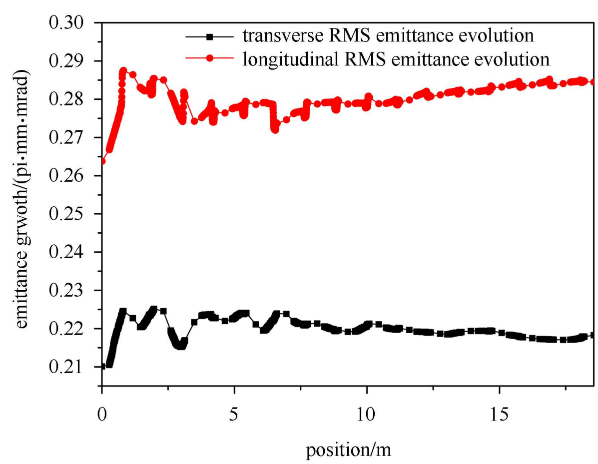

Fig. 7. The RMS emittance evolution along the SC section.

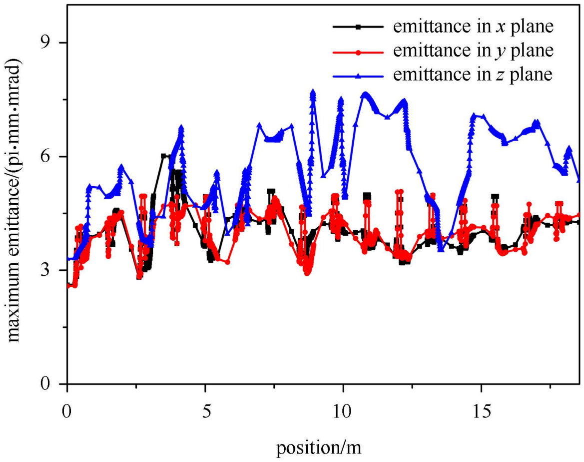

Fig. 8. The maximum emittance evolution along the SC section.

using the TraceWin [10] code. The 2D PICNIC space charge routine with a 30×50 mesh is employed for space charge calculations. Fig. 7 and Fig. 8 show the RMS emittance growth and maximum emittance evolution along the SC section, respectively.

From the multi-particle simulation results, the transverse RMS emittance growth is 4%, and the longitudinal RMS emittance growth is about 2%. The RMS emittance growth along the main linac is acceptable in all of the three phase spaces. The emittance growths for 100% beam fraction are 44.7%, 25.1%, 61.8% in three planes, respectively. The maximum emittance is affected by the halo particles, which lie in the low density region of the beam distribution, far away from the core. In general, there are various effects which may cause beam distribution change, such as beam mismatch, space charge coupling resonance, off-axis motion and so on. Among all of these mechanism, the coupled effects caused by mismatch, nonlinear space charge and external field are considered as the major reasons of emittance and halo formation. The mismatched beam will oscillate due to the unbalance between the external focusing force and intrinsic defocusing force related to space charge. During this process some particles may get energy to manipulate the unwanted space and beam halos are formed, which is accompanied with filamentation and emittance growth or even beam loss. The evolution of the beam halo is complex, and a more detailed study will be done in the future.

6 Summary

In this paper a full period lattice structure design for the SC section of C-ADS injector scheme Ⅱ has been presented. The design philosophy and consideration are demonstrated and a detailed design is also discussed. The SC section of injector scheme Ⅱ incorporates 16 HWR cavities and 16 superconducting solenoids surrounded in four cryomodules. The total length of this SC section is 18.56 m. Multi-particle simulation results with realistic particle distribution out of the RFQ are shown. The emittance growths are 6%, 4% and 2% in the x, y and z planes, respectively. Halo emittance growths are 44.7%, 25.1% and 61.8% in three plane phases, respectively. Further optimizations and other discussions will be carried out in the future.

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