CPC(HEP & NP), 2012, **36**(3): 256–260 Chinese Physics C Vol. 36, No. 3, Mar., 2012

The design simulation of the superconducting section in the ADS injector Ⅱ *

WANG Zhi-Jun(王志军)[1,2,3;1)] HE Yuan(何源)[1,3;2)] LIU Yong(刘勇)[3)]
YUE Wei-Ming(岳伟明)[3)] YANG Xiao-Liang(杨晓亮)[1,3)] WU Wei(吴巍)[3]
LI Chao(李超)[1,3] XIAO Chen(肖陈)[1,3] JIA Huan(贾欢)[1,3]

[1] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[2] The School of Nuclear Science and Technology Lanzhou University, Lanzhou 730000, China
[3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: The high-current superconducting proton linac is being studied for the accelerator-driven system (ADS) project undertaken by the Chinese Academy of Sciences. The injector Ⅱ will be operated at 162.5 MHz, and the proton out from the RFQ with an energy of 2.5 MeV will be accelerated to 10 MeV by two cryo-modules, which are composed of eight superconducting half wave resonance cavities and nine solenoids. In this paper, the design and beam simulation of the superconducting section of the injector Ⅱ, the acceptance calculation and a stability analysis are presented.

Key words: ADS injector Ⅱ, high-current linac, acceptance calculation, Hofmann stability chart

PACS: 29.27.Bd, 52.65.Rr, 41.20.cv **DOI:** 10.1088/1674-1137/36/3/012

1 Introduction

Nuclear energy as a clean energy will be widely used in the Chinese energy program in the future. But one of the main problems is how to handle the radioactive waste produced by nuclear plants. The accelerator-driven system (ADS), which is an effective tool for transmuting the long-lived transuranic radionuclides into shorter-lived radionuclides, is being studied at the Chinese Academy of Sciences. The roadmap of the project is shown in Fig. 1.

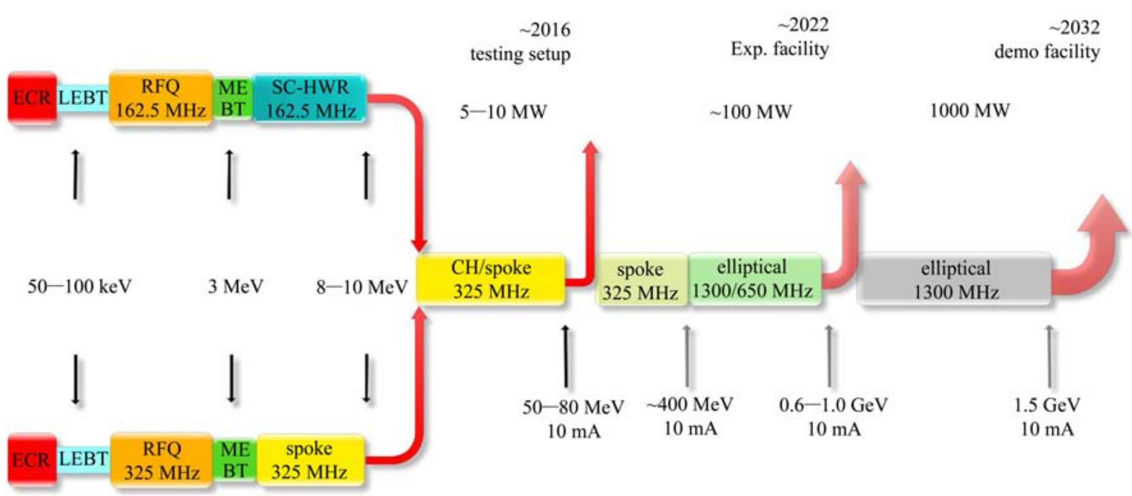

Fig. 1. (color noline) The roadmap of the China CAS project.

Received 14 March 2011
∗ Supported by National Natural Science Foundation of China (11079001)
1) E-mail: wangzj@impcas.ac.cn
2) E-mail: hey@impcas.ac.cn

The linac will accelerate protons with a beam current of 10mA to about 1 GeV to produce high flux neutrons for the transmutation of nuclear waste.

To ensure technical feasibility in the low-energy section, two injectors for the superconducting (SC) linac are designed during the first step. The basic parameters of the injector Ⅱ are listed in Table 1.

Table 1. The basic parameters of the injector Ⅱ.

parameter	value
particle type	proton
operation frequency/MHz	162.5
operation mode	CW
beam kinetic energy/MeV	10
beam current/mA	10

In this paper, the design and simulation results of the SC section in the injector Ⅱ are presented.

2 The layout of the SC section

The SC section will accelerate the proton from 2.5 to 10 MeV using the two same cryo-modules. Each cryo-module is composed of eight SC half wave resonance (HWR) cavities and SC solenoids. The main parameters of the cavity and solenoid are shown in Table 2.

Table 2. The main parameters of the SC cavity and the solenoid in the injector Ⅱ.

parameter	value
SC HWR cavity beta value	0.09
Ep at 1.0 J/(MV/u)	12.5
Bp at 1.0 J/mT	25
Q_0 at 4.4 K value	1.40E+09
R_a/Q_0	148
W_{diss}/W at 4.4 K	2.9
operation temperature/K	4.4
length/mm (flange to flange)	210
SC solenoid effective length/mm	150
center field/T	7.5
operation temperature/K	4.4

The SC cavity is selected for its advantages of low RF loss and high accelerating gradient, and the SC solenoid is chosen to offer a transverse focusing force at the low energy section. The SC solenoid can offer a high focusing gradient with shorter length compared with the quadrupoles [1]. Another advantage, which is very important to the high-current machine, is that the solenoid is less sensitive to misalignment errors and beam mismatch. The layout of the cryo-modules is shown in Fig. 2.

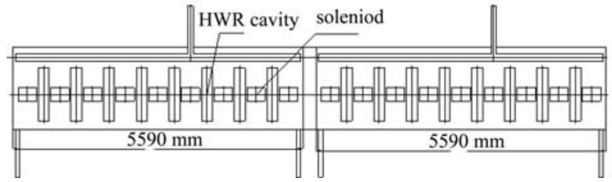

Fig. 2. The layout of the cryo-modules.

As shown in Fig. 2, cold transition is considered between two cryo-modules to reduce the drift length. This is beneficial to beam dynamics at low energy. The focusing period, which is composed by one solenoid and a resonator, can provide strong focusing at low beam energy and is important in terms of minimizing the core emittance growth and beam halo generation [2].

3 Design rules for the high-current proton linac

The design of the SC section of the injector Ⅱ was undertaken using the following rules for the high-intensity proton linac, so as to avoid emittance growth and envelope instability.

(1) The phase advance at zero current beam in transverse σ_{t0} and longitudinal σ_{l0} should be lower than 90° per focusing period to avoid envelope instability at high current [3].

(2) Nonlinear parametric resonance should be avoided when $f_{particles} = f_{mode}/2$, where $f_{particles}$ is the betatron frequency and f_{mode} is the mode-oscillation frequency [4].

(3) The wave number in the transverse and longitudinal, κ_{t0} and κ_{l0}, which means the strength of focusing force in each period, should change smoothly along the whole linac. This will decrease the risk of mismatch and make the linac less sensitive to the beam current. This rule is very important at the transition section, where the periods are broken due to the practical limit in cryo-module length or the change in SC cavity family. The wave numbers κ_{t0} and κ_{l0} are expressed as follows [5].

$$\sigma_{t0} = \frac{\kappa_{t0}}{L_0}, \quad \sigma_{l0} = \frac{\kappa_{l0}}{L_0}, \tag{1}$$

where L_0 means the length of the focusing period.

(4) The energy exchange between the transverse and longitudinal directions by space charge resonances should be avoided. The work point of each cell should be at a location far from the unstable area [6].

(5) The matching between transition sections should be accurate to avoid beam halo formation.

The envelope should be as smooth as possible at the transitions and keep off the high peaks in the envelop along the linac.

4 Beam dynamics of the SC section

The beam dynamics of the SC section was performed by the TraceWin code [7], which was developed by CEA Saclay. The code is used for linear (matrix) and nonlinear calculations (macro-particle transport with Partran library) for 2-D or 3-D electrons or ions beam. The beam is simulated with a field map of the cavities and solenoids acquired from the 3-D finite elements Micro Wave Studio (MWS) [8] and Opera3D [9] software.

The initial emittance is obtained from the output of the RFQ simulation. 50000 particles, which are initialized as Gauss distribution, are tracked at zero and 10 mA. Some simulation and analysis results are presented as follows.

4.1 The phase advance and envelop along the SC section

The transverse and longitudinal phase advance at zero current in each focusing period are depicted in Fig. 3.

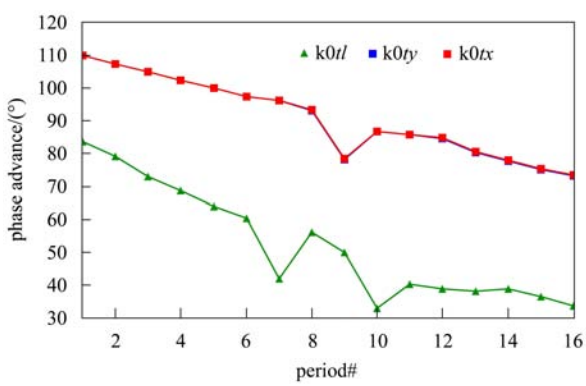

Fig. 3. (color noline) The phase advance of each period at zero current.

There are some jumps at the transition section because the periodic lattice is broken by splitting the cryo-module into two parts. Four cavities and three solenoids adjoined are adjusted to perform the match between the two cryo-modules in order to avoid the appearance of a high peak at the transition section in both the transverse and longitudinal planes.

The rms envelop along the linac is plotted in Fig. 4. When the beam is symmetric in the x and y direction, the envelopes of x and y are the same as shown in the above part. While in the blew part, the vertical axis is RMS bunch length in degree. Also, we can see that the envelope at the transition section is smooth and there is no high peak, which means that the match section is not sensitive to errors.

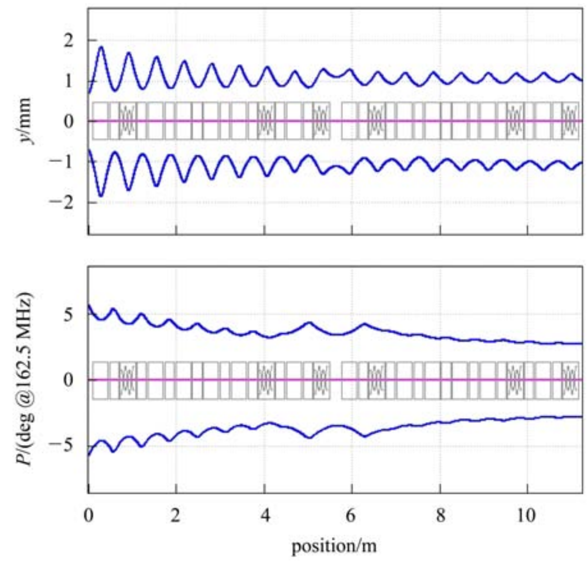

Fig. 4. The envelope at a 10 mA current along z.

4.2 Acceptance analysis of the SC section

The longitudinal acceptance of the SC section is analyzed with the TraceWin code at zero current. The initial longitudinal emittance is set to be large enough. In our analysis, particles whose energy spread is larger than 0.5 MeV and phase spread is larger than 120° are set as lost particles. These particles, which can track through the lattice, are used to calculate the acceptance. The acceptance is plotted in Fig. 5.

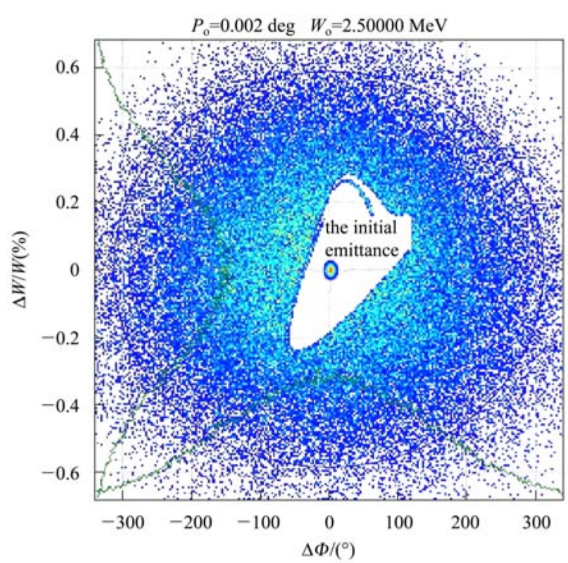

Fig. 5. The acceptance of the SC section.

As shown in Fig. 5, the blank part is the acceptance of the linac at 162.5 MHz. In the chart, the horizontal axis is the phase spread in degrees and the vertical axis is the energy spread. The emittance is also plotted in the center of the acceptance. The ratio of the acceptance and the emittance is about 20 times, so there is a large margin of acceptance.

4.3 Stability analysis of the SC section

An important parameter to evaluate the high-current linac is the tune depression, η, which is the ratio of wave number per focusing with and without space charge. The tune depression is a useful tool to quantify the parametric resonance and coherent resonance. A common tool called the Hofmann chart [4] is used to analyze the core–core resonance. For the given ratio of longitudinal emittance over transverse emittance, the region where the non-equipartition beam can stably operate is indicated from the Hofmann Chart. The Hofmann chart with a longitudinal to transverse emittance ratio of $\epsilon_{\rm l}/\epsilon_{\rm t}$=1.68 is presented in Fig. 6.

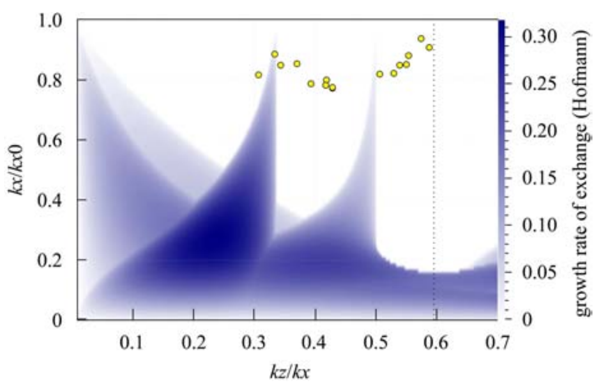

Fig. 6. Hofmann chart of the SC section in the ADS injector Ⅱ.

In the chart, the horizontal axis is the ratio of phase advance with space charge between longitudinal $\kappa_{\rm l}$ and transverse $\kappa_{\rm t}$, and the vertical axis $\kappa_{\rm t}/\kappa_{\rm t0}$ is the tune depression in the transverse. The stability of the SC section at the designed beam current of 10 mA can be characterized. The shaded areas shows where the non-equipartition beam will experience space charge coupling resonances, and the degree of shading indicates the speed of the coupling resonances [10]. From Fig. 6, we can see that some tune points are located at weak coupling resonance regions, so it will take a long time to develop coupling. It should be pointed out that space charge coupling resonances are not an issue for this linac operating at 10 mA beam current.

The main parameters of the design results are listed in Table 3.

Table 3. Summary of the parameters in the injector Ⅱ.

parameters	value
ϵ_{it}/π·mm·mrad	0.25
ϵ_{il}/π·mm·mrad	0.42
growth of $\epsilon_{\rm t}$ (%)	3.2
growth of $\epsilon_{\rm l}$ (%)	2.0
growth of 0.99$\epsilon_{\rm t}$ (%)	10.0
growth of 0.99$\epsilon_{\rm l}$ (%)	6.1
$A/t_{\max}$	8.49
$\phi_{\rm s}/l_{\max}$	7.78
length of per focusing period/mm	630
number of cavities	16
number of solenoids	18
total length/m	11.2

Where, in Table 3, ϵ_{it} is the initial normalized rms emittance in the transverse, and ϵ_{il} in the longitudinal; 0.99$\epsilon_{\rm t}$ is the normalized emittance including 99% of the particles in the transverse direction, and 0.99$\epsilon_{\rm t}$ in the longitudinal direction; A is the aperture of the cavity, and $t_{\max}$ is the max value of the rms envelope in the transverse along z, $\phi_{\rm s}$ is the synchronous phase, and $l_{\max}$ is the max value of the bunch length along z.

5 Summary

In this paper, the design of the SC section of the ADS injector Ⅱ is presented. The acceptance and the Hofmann stability of the lattice are also analyzed, and the results show that the design has a large acceptance in both the transverse and longitudinal phase space. In addition, from the Hofmann chart, the operation tune has a large margin of core-core space charge resonances. Further work on error simulation will be performed next.

One of the authors, Zhijun Wang, would like to express his sincere thanks to Jean-Francois Ostiguy (FNAL), Jean-Paul Carneiro (FNAL), Nagaitsev Sergei (FANL) and Zhihui Li (IHEP) for their useful discussions about beam dynamics, the high-current linac and the use of the TraceWin code.

References

1 Ostroumov P N, Carneiro J P. Physics Design of Front-ends for Superconducting Ions Linacs. Proceedings of the Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams. Nashville, Tennessee, 2008. http://lss.fnal.gov/cgi-bin/find_paper.pl?pub-09-034.pdf

2 Lawrence G P. High-Power Proton Linac for APT; Status of Design and Development. Linac98 Proceedings, 26–30, 1998. http://www.aps.anl.gov/News/Conferences/1998/LINAC98/papers/MO2002.pdf

3 Martin Reiser. Theory and Design of Charged Parcle Beam. 2nd. New York: Wiley, 2008

4 Allen C K, Chan K C D, Colestock P L et al. Phusical Review Letter, 2002, **V89**: 21

5 Nath S, Crandall K, Gray E et al. Beam Dynamic Aspects for the APT Integrated Linac, 1997, **1**: 1162–1164

6 Thomas P Wangler. RF Linear Accelerators. 2nd. New York: Wiley, 2008

7 Uriot D. TraceWindocumentation, http://irfu.cea.fr/Sacm/logiciels/index3.php,2011

8 http://www.cst.com/Content/Products/MWS/Overview.aspx. A specialist tool for the 3D EM simulation of high frequency components,2011

9 http://www.cobham.com/about-cobham/aerospace-and-security/about-us/antenna-systems/kidlington/products/opera-3d.aspx. Opera-3d electromagnetic design in three dimensions, 2011

10 Carneiro J P, Mustapha B, Ostroumov P N. Nuclear Instruments and Methods in Physics Research A, 2009, **271–280**: 1178–1181