Chinese Physics C Vol. 37, No. 2 (2013) 027002

Design study of the SSC-LINAC re-buncher *

SUN Lie-Peng(孙列鹏)[1,2,1)] ZHAO Hong-Wei(赵红卫)[1] SUN Guo-Ping(孙国平)[1] HE Yuan(何源)[1]
SHI Ai-Min(石爱民)[1] XIAO Chen(肖陈)[1,2] DU Xiao-Nan(杜小楠)[1,2]
ZHANG Cong(张聪)[1,2] ZHANG Zhou-Li(张周礼)[1,2]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: A re-buncher with spiral arms for a heavy ion linear accelerator named as SSC-LINAC at HIRFL (the heavy ion research facility of Lanzhou) has been constructed. The re-buncher, which is used for beam longitudinal modulation and matching between the RFQ and DTL, is designed to be operated in continuous wave (CW) mode at the Medium-Energy Beam-Transport (MEBT) line to maintain the beam intensity and quality. Because of the longitudinal space limitation, the re-buncher has to be very compact and will be built with four gaps. We determined the key parameters of the re-buncher cavity from the simulations using Microwave Studio software, such as the resonant frequency, the quality factor Q and the shunt impedance. The detailed design of a 53.667 MHz spiral cavity and measurement results of its prototype will be presented.

Key words: re-buncher, cavity, quarter wave resonator, spiral structure

PACS: 29.27.Bd, 52.65.Rr, 41.20.cv **DOI:** 10.1088/1674-1137/37/2/027002

1 Introduction

The spiral cavity is a special type of RF structure other than the QWR (quarter wave resonator). Its remarkable properties are of high efficiency, compact structure and great rich harmonic field components [1]. Furthermore it can easily be tuned to target frequencies by varying its length. Of course, the compact design can also reduce the overall budget significantly. This re-buncher resonator operates at a fixed frequency of 53.667 MHz to provide the longitudinal focusing for a 7.12 MeV heavy ion beam. To reduce the risk of sparking, the gap voltage is carefully optimized at 30 kV. The bunching voltage, which is defined as the sum of the four gap voltages, has reached 120 kV at a power consumption of 3.2 kW.

According to the dynamics design of LINAC [2], the re-buncher is located between the RFQ and the DTL cavities, and adopted to provide adjustable longitudinal focusing force to guarantee that most particles do not exceed the longitudinal acceptance of the DTL. The longitudinal energy spread with the main bunch on and off the DTL at the entrance of the DTL is illustrated in the left and right figures of Fig. 1, respectively.

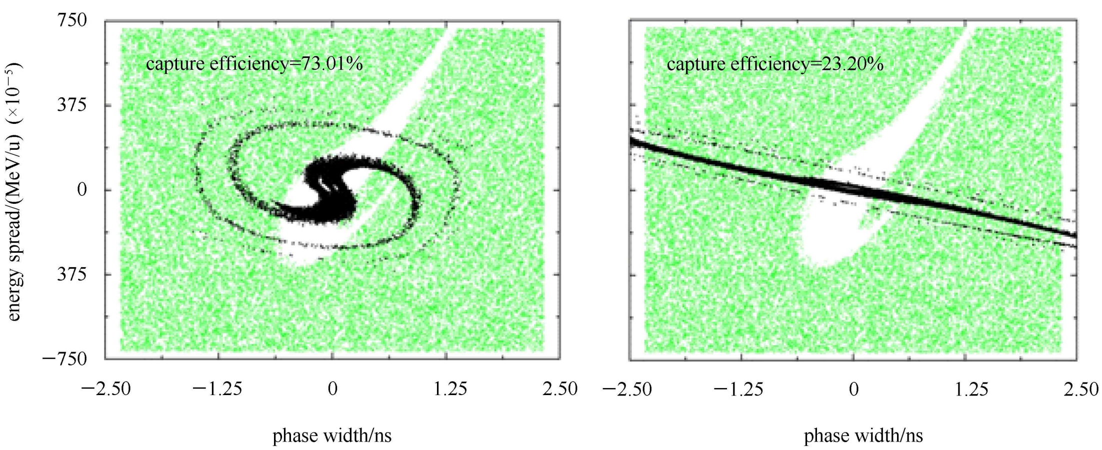

Fig. 1. The particle longitudinal distribution when the re-buncher is turned on (left) and off (right) respectively.

Received 14 September 2011, Revised 19 May 2012
* Supported by Pioneering and Interdisciplinary Research of Big Sciences (Y115210YQ0)
1) E-mail: sunlp@impcas.ac.cn

The large void region is the longitudinal acceptance of the whole DTL. The area occupied by black dots is the matched longitudinal particle distribution at the entrance of the DTL. Obviously, without the bunching function, the majority of the particles will be lost and only 23.2% of the particles can be accelerated by the DTL. When the re-buncher is turned on, a satisfactory result can be acquired by optimizing the re-buncher structure and its bunching voltages.

2 Specification

According to the theoretical calculation the working frequency of the re-buncher is 53.667 MHz. If we use the QWR structure, at this frequency it is very difficult to bunch the beam into a limited longitudinal spacing of only 20 cm. So, we determine to adopt the spiral structure instead.

There have been many spiral cavities developed for different purposes throughout the world in the past two decades [3]. These cavities are used for acceleration, debunching and bunching. The frequency range can be from 27 MHz to 200 MHz for the particle energy from 10 keV/A to about 50 MeV/A. The maximum shunt impedance can reach as high as 60 MΩ/m, thus these cavities have little power consumption and work stably.

Since the re-buncher operates in CW mode, the cooling is our primary concern, and special attention must be paid to its vibration problem originating from the water flow and other sources. The parameters of the cavity are shown in Table 1.

Table 1. The parameters of dynamics design.

specification	value
resonant frequency, f/MHz	53.667
velocity, β	0.0175
charge to mass ratio	1/7
operating energy/(MeV/u)	0.143
accelerating voltage, V/(kV/gap)	30
length of cavity, $\beta\lambda$/cm	22.9
tank diameter/cm	60
diameter of aperture/cm	3.4
voltage stability	±1%
phase stability	±0.3%
vibration amplitude/mm	±0.1
operating mode	CW

3 Calculation and consideration

3.1 Transit time factor (TTF) [4]

The TTF indicates the effective voltage of a resonator for particles passing through. For the multi-gap cavities, the shunt impedance is proportional to the gap number, and in the case of the single-spiral structure, it is proportional to the square of the gap width.

The TTF is the product of a velocity-dependent term $T_{\rm V}$ and a geometry- dependent term $T_{\rm G}$:

$$T_{\rm G}=\frac{\beta\lambda}{\pi(d+0.85r)}\sin\left(\frac{0.85\pi r}{\beta\lambda}\right)\frac{1}{I_0\left(\dfrac{2a\pi}{\beta\lambda}\right)}, \tag{1}$$

$$T_{\rm V}=\frac{2\beta}{n\pi(\beta/\beta_0)}\sin\left(\frac{n\pi(\beta/\beta_0)}{2\beta}\right), \tag{2}$$

where n means the gap number, β is the relativistic velocity, d is the width of the acceleration gap, r is the radius of the drift tubes and a is the radius of the aperture.

The wide spectrum of possible selections is clearly shown in Fig. 2, so the multi-gap structures are limited to a narrow energy interval. Obviously, the total voltage $U_{\rm tot}$ can be reduced when n is large for a fixed $(n*TTF*U_{\rm tot})$ [5]. However, the phase width of the beam bunch in the re-buncher is also proportional to n, which suggests that the beam is not effectively captured in the RF bucket if n is too large.

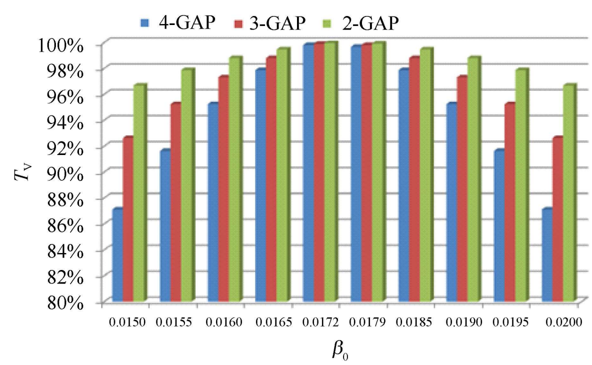

Fig. 2. TTF of the multi-gap spiral cavity.

3.2 Calculation

By means of the equivalent resonant circuit analysis, an efficient optimization procedure is to make a set of simplified estimations at first and then we compare the calculated values with the simulated results. First, the quality factor Q can be estimated as: $Q=\omega U/P$, where ω is the angular frequency of the mode and U is the stored energy in the system, and P the average power loss. They can be calculated by the following expressions [6]:

$$U = \frac{1}{2}\mu_0\int|H|^2{\rm d}V, \tag{3}$$

$$P = \frac{1}{2}R_{\rm S}\int|H|^2{\rm d}S, \tag{4}$$

where $R_{\rm S}$ is the average surface resistance of the material. The quality factor Q indicates the power loss in the structure. Second, the high shunt impedance or shunt impedance per unit length [7], which is the figure of merit of the accelerating efficiency and independent of the excitation level of a cavity, can be estimated as:

$$R = \frac{V_0^2}{P}, \tag{5}$$

$$Z = \frac{R}{l}, \tag{6}$$

$$V_0 = \left|\int^0 E_Z(Z)\mathrm{d}Z\right| + \left|\int_0^L E_Z(Z)\mathrm{d}Z\right|, \tag{7}$$

where V_0 is the bunching voltage [8], P is the dissipation power of the cavity, l is the cavity length and E_Z is the bunching electric field. It indicates how much energy is needed to establish a certain average electric field inside the cavity. Finally, we can determine the specific dimension by using the electromagnetic modeling software. According to the simulated results, the TTF, R, Z and Q-factor values are 0.8909, 2.248 MΩ, 11.24 MΩ/m and 3861 respectively.

3.3 Consideration of structure

Since the dynamics design of the bunching gaps is the first step of the structural design, the gap voltage is the key factor in consideration, and this has been confirmed by KILPARTRIC's criterion for vacuum sparking, which shows the relationship between the breakdown electric field strength of gaps and the frequency as:

$$f(\mathrm{MHz}) = 1.627E^2\exp(-8.51E(\mathrm{MV/m})). \tag{8}$$

According to Formula (8), the KILPARTRIC factor is about 1.05. In other words, there is only a little chance of RF breakdown,and this structure has a great potential to increase the electric field strength. The next work is the determination of the structure dimensions by taking into account all the factors of cavity design, such as the sparking,the high shunt impedance,the voltage distribution, the Q factor, the TTF, etc.The structure parameters of the tubes determined by the systematic optimization, together with the longitudinal spacing which has been taken into account in the dynamics design, are shown in Fig. 3.

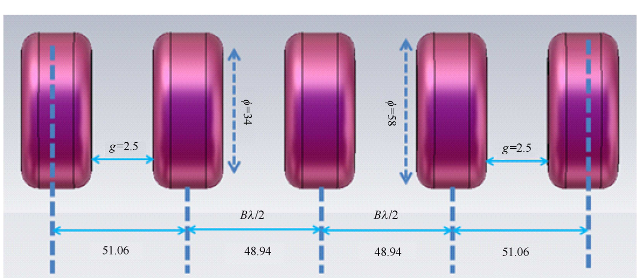

Fig. 3. Geometry and dimensions of the tubes and gaps.

4 Simulation

4.1 Simulation results

The main results of the dynamics simulation for the complicated multi-gap resonator using RF design software named Microwave Studio are presented in Table 2.

Table 2. The simulated results.

characteristic parameters	results
resonant frequency/MHz	53.7676
total energy/joule	1
total power loss/kW	83.04
shunt impedance/kΩ	2248
gap voltage/kV	227.38
$(R/Q)/\Omega$	153.044
Q-factor	4068.2

The main consideration for cooling is to analyze the surface current distribution [9] which is indispensable to the structural and thermal designs. Another concern is the voltage distribution along z-axis shown in Fig. 4.

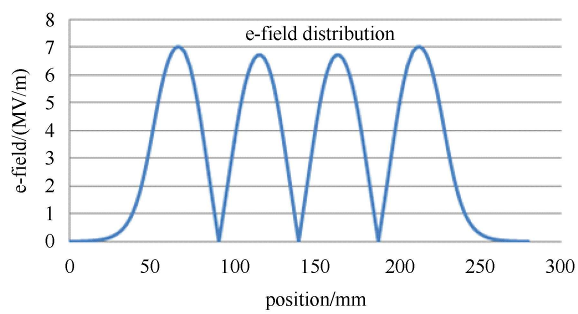

Fig. 4. Simulation of the voltage distribution.

4.2 Simulation analysis

The dimensions of the gaps and tubes can be determined from the beam dynamics, and it is equal to the product of relativistic velocity β and wavelength λ. Thus only the outer dimensions of the tubes need to be adjusted in the simulation to optimize the shunt impedance and frequency of the cavity [10]. Fig. 10 shows the optimized results.

4.3 Simulation concerning the cavity power

The power consumption of the cavity can be estimated easily from the above calculated results. First of all, the shunt impedance of four gaps R (about 2248 kΩ) is a key factor. According to the simulated results and the design voltage of each accelerating gap, the magnitude of total power consumption of the cavity can be estimated roughly by using Eq. (9):

$$P = (16V_{\mathrm{gap}}^2/2R) = 3.203\ \mathrm{kW}. \tag{9}$$

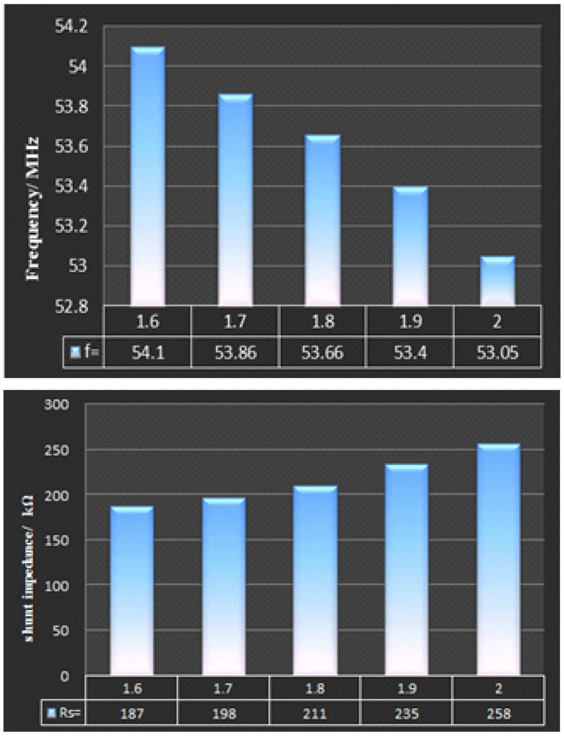

Fig. 5. The influences of outer diameter [9] of the tubes.

The calculated results show the power loss on the cavity is about 3 kW. We can also estimate the cavity power loss which usually accounts for the power margin, thus a 10 kW amplifier is needed.

4.4 Coupling loop [5]

The RF power will be fed into this cavity by a coupling loop which is located near the root of the spiral. The loop area of 100 cm^2 will provide impedance matching of 50 Ω. Now this coupler has been designed and simulated at IMP.

5 Measurement of the prototype cavity

By May 2011 the prototype cavity had already been manufactured at IMP. The inside structures are presented in Fig. 6.

Considering the cavity cost, we decided to choose the carburizing steel for the outer housing and the aluminum for the inner conductor. The measurement results are shown in Table 3 and Fig. 7.

Table 3. Measurement results.

characteristic parameters	measured results
resonant frequency/MHz	53.678
scattering parameter (S_{11})/dB	−24
tuning range/kHz	±152
$(R/Q)/\Omega$	142.5
Q-factor	702
flatness of electric field	⩽2.65%

Fig. 6. A view of inside the prototype resonator.

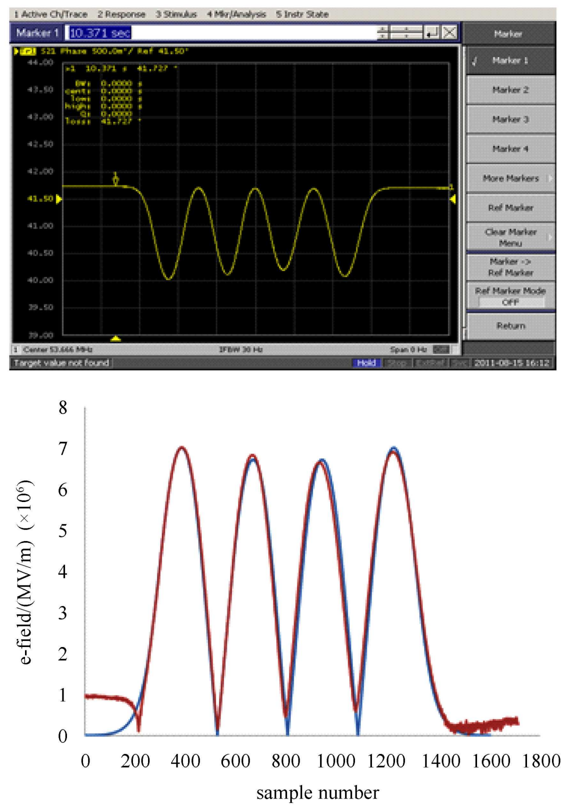

Fig. 7. Measurements and analysis of the electric field flatness, the upper figure shows the measured results of the phase shift and the following figure is the comparison between the simulated results (blue line) and the measured results (red line).

6 Summary

From the measured Q value as above, we found that the material conductivity could be the primary problem. Through analyzing the power loss in the lossy resonator presented in Fig. 8, it is realized that the spiral arms and wall consume the majority of the RF power. The materials of the prototype are the carburizing steel and duralumin with low conductivity. Using these materials, the simulated Q-factor is no more than 1200. According to the simulations and measurements, we think that a copper spiral cavity will improve its performance greatly, especially for the Q value and shunt impedance. Of course, a good contact and careful assembly are not to be neglected.

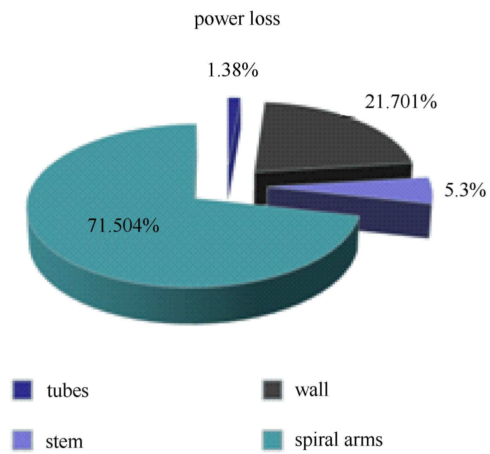

Fig. 8. The power loss of the cavity.

The re-buncher at the MEBT is very important for the longitudinal matching between the DTL and the RFQ cavity. The RF performance of the cavity with two spiral arms has been simulated. Now a full-scale prototype has already been manufactured. The primary measurement shows that the re-buncher design can meet the requirements of the linear accelerator. Although the Q factor is only 702, a little far away from the original design, this value agrees well with the calculated value of the lossy metallic material. In addition, the trajectory tracking results based on the electromagnetic simulation have been finished to help understand the dynamics process. Now further study of various properties for this cavity is in progress, including all the basic tests using a vector network analyzer and the bead-pull measurement [11]. Then, a lot of work still needs to be done, including fabricating a solid-state amplifier and developing a real copper cavity.

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