Study on Superconducting Quarter Wave Resonator for CW Intense Ion Linac

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Abstract

Superconducting coaxial quarter wave resonator (λ/4 cavity) is used for low beta ion linacs. But it should be carefully used for cw intense machines because its accelerating electric field on beam axis has weak dipole component and consequently there is a possibility of the emittance growth causing beam spill. In order to investigate the applicability of λ/4 cavity to cw intense machines, we developed a preliminary simulation code using the actual electromagnetic (EM) field distribution without space charge effect. We applied this simulation code to a superconducting linear accelerator (sc linac) with λ/4 cavities. As a result, it is found that the transverse emittance becomes somewhat large, and the design of HEBT should include this influence. Besides we mention the longitudinal emittance growth attributed to the partial missing of the sc cavities in the sc linac.

1 INTRODUCTION

Intense proton or deuteron cw sc linac have been proposed for irradiation tests of materials for future fusion devices[1] and transmutation of nuclear waste[2]. Compared with a conventional room temperature linac, the sc linac is considered to be promising because it can drastically reduce large amount of heat loss and required rf power [3].

The beam spill in the sc linac is severely restricted to minimize radio-activation of the machine. The preliminary design study was carried out for the sc linac in which the ./2 coaxial cavity with two gaps was applied because its accelerating electric field is symmetric on the beam axis [4]. Of course, if the asymmetric electric field is within allowable level, the ./4 cavity with two gaps will be preferable due to its compact structure and less surface rf loss.

In order to evaluate the influence of the asymmetric electric field on the beam behaviour, we developed a beam simulation code using the actual electric field calculated by the three-dimensional EM analysis code, MAFIA. In this paper, the principle of the simulation, design of the ./4 cavity and calculation results for the ./4 linac system are presented.

2 SIMULATION CODE

We developed a simulation code applying the actual EM field and simple impulse approximation without space charge effect.

2.1 Calculation of EM field

The EM field in the asymmetrical structures has been calculated by the three-dimensional code MAFIA.

The EM field vector $\vec{E}(E_x,E_y,E_z)$ and $\vec{B}(B_x,B_y,B_z)$ are given in the interval of 5mm for z direction and 2mm for both x and y directions. The coordinate is shown in Fig.1. The actual field used for the beam simulation is obtained by an interpolation of the 8 mesh points data surrounding a particle.

2.2 Impulse approximation

The basic formula of simulation code is as follows. The equation of motion in EM field is given in (1) and modified as (2):

$$\frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{1}$$

$$\beta \mathrm{cm}\gamma \Delta\vec{v} = q(\vec{E} + \vec{v} \times \vec{B})\Delta z \tag{2}$$

The velocity of the particle at the exit of the cavity, $\vec{v}_f$ can be written:

$$\vec{v}_f = \vec{v}_i + \int \frac{q(\vec{E} + \vec{v} \times \vec{B})}{\beta \mathrm{cm}\gamma} dz$$
$$\approx \vec{v}_i + \sum_j \frac{q\left[\vec{E}(j\Delta z) + \vec{v} \times \vec{B}(j\Delta z)\right]\Delta z}{\beta_j \mathrm{cm}\gamma_j} \tag{3}$$

where,

$$\vec{E} = \vec{E}(x,y,z) \times sin(\frac{2\pi fz}{v} + \phi)$$
$$\vec{B} = \vec{B}(x,y,z) \times sin(\frac{2\pi fz}{v} + \phi + \frac{\pi}{2}).$$

3 THE DESIGN OF THE SC CAVITY

3.1 Major specifications for the design

The following major specifications were considered for the design of the SC linac system.

(1)Particle	D^+
(2)Energy range	8-40 MeV (β = 0.092-0.203)
(3)Beam current	125 mA
(4)Accelerating frequency	175 MHz
(5)Duty factor	cw

It was assumed that a high energy RFQ is used as an injector to the sc linac. High output beam energy of 8

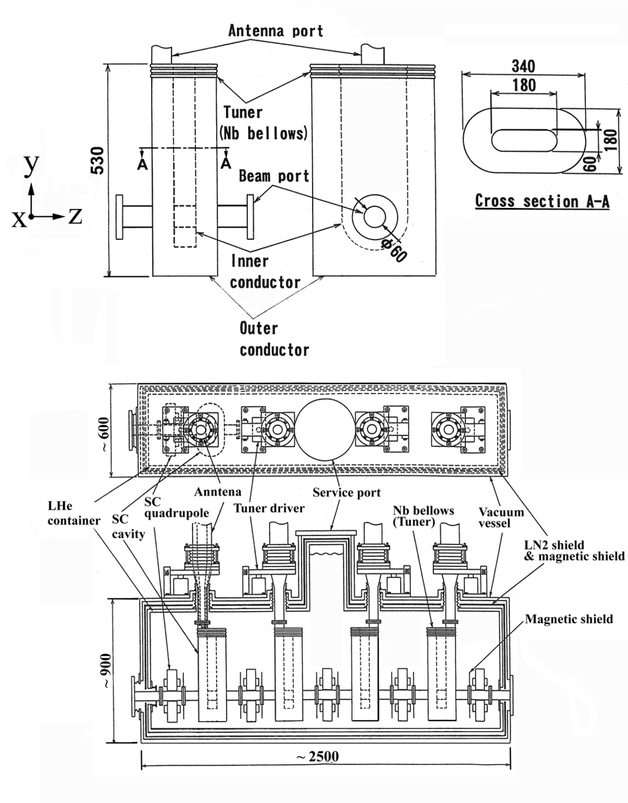

Fig.1 Schematic drawings of one λ/4 cavity and one cryomodule.

MeV necessitates an unconventional long RFQ structure but it enables to apply the sc linac at low β region.

3.2 Structure of the cavity and cryomodule

The schematic drawings of one λ/4 cavity and one cryomodule are shown in Fig. 1. The cavity made of niobium(Nb) consists of an inner conductor and an outer conductor. Both conductors have the height of about ./4 and the cross section of race track configuration. The cavity has the same shape as that of the λ/2 cavity in the previous paper[4] except that the lower part of the inner conductor is cut off and rounded. When the z component of the average accelerating field per half cell, E_{acc}, is 3.5MV/m, E_{max} and B_{max} are 34MV/m and 800Gauss, respectively. These values are about two times as high as those in the λ/2 cavity. The y component of the average accelerating field, $\overline{E}_y$ which acts as dipole field and causes beam oscillation, is ~1% of E_{acc}. Though B_{max} is enough small compared with the critical magntic field of 1500Gauss at 4.2K, the cavity shape should be optimized so as to reduce E_{max}/E_{acc} (B_{max}/E_{acc}) including $\overline{E}_y/E_{acc}$, if neccesary.

In one cryomodule, Four cavities are accommodated and each cavity has an antenna with a rf window which is not shown in Fig. 1. Five superconducting quadrupole magnets with magnetic shields are located at both sides of the rf cavities in the cryomodule.

Table1 specifications of sc cavity and sc quadrupole magnet

(SC cavity)	
Material	Nb
Frequency	175 MHz
Thickness of inner conductor	60 mm
Gap length	60 mm
Width of outer conductor	180 mm
Length of outer conductor	340 mm
Q value*	1.5×10^9 ($7.5\times10^{8**}$)
E_{max}/E_{acc}	9.6 (4.0^{**})
B_{max}/E_{acc}	2.3×10^{-2} ($1.2\times10^{-2**}$) T/(MV/m)
$\overline{E}_y{}^{***}/E_{acc}$	~0.01
Height	530 mm
(SC quadrupole magnet)	
Bore diameter	60 mm
Magnet length	80 mm
Magnetic field gradient	max 60 T/m

* : the surface resistance of Nb is assumed to be 50nΩ
** : the values of the λ/2cavity.
*** : y component of average electric field per half cell

Main specifications are summarized in Table 1.

4 BEAM SIMULATION AND RESULTS

4.1 Beam simulation conditions

The beam parameters of the RFQ output[1] and the sc linac conditions are assumed as shown in Table 2. The RFQ output assumed to be Gaussian distribution and cut out at 4 standard deviations, is applied to the initial beam distribution. On the other hand, the sc linac conditions are decided based on the previous simulation for the one with the λ/2 cavities[4]. The assumed sc linac has a structure connected with 12 cryomodules shown in Fig.1. This structure enables the interval between the quadrupole magnets to keep constant anywhere. The resultant simulation structure is that both the cavities and

Table 2 beam parameters of the RFQ output and sc linac conditions

(RFQ output)	
Input energy	8MeV
Norm. rms transverse emittance	0.4 π mm mrad
Norm. rms longitudinal emittance	0.8 π mm mrad
(sc linac)	
Number of cryomodules	12
E_{acc}	2.5~3.5 MeV/m
Synchronous phase	-35 deg
Number of particles	10000
Output energy	~42 MeV
Magnet field gradient	20~40 T/m
Interval between quadrupole. magnets	53 cm

quadurpole magnets are placed at regular intervals of 53 cm and rf acceleration field is missed every 5 cavities.

4.2 Results and Discussions

Beam profiles about x, y, $\Delta\phi$ and ΔW are shown in Fig.2. The maximum beam diameter is about half the beam bore of ϕ60mm. The beam behavior is roughly similar to the one in the $\lambda/2$ cavity. However, since the beam oscillates in y direction owing to the asymmetrical field, as shown in Fig.3, the substantial emittance(ε_y) observed from the beam transport axis becomes somewhat larger than that observed from the beam center. In Fig.3, rms emittances are expressed as follows:

$$\varepsilon_{\mathrm{rms}} = \frac{1}{4}\sqrt{\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2}$$

Therefore HEBT must be designed taking account of this increase of the emittance.

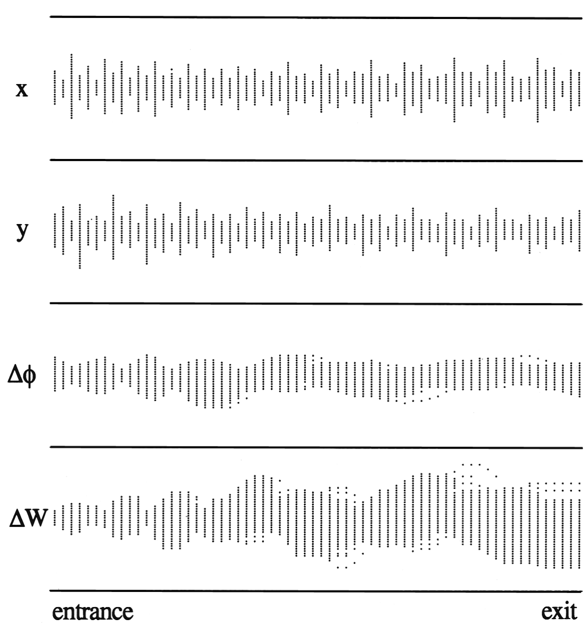

Fig.2 beam profiles along the SC linac
ranges x: -30 and 30mm, y:-30 and 30mm
$\Delta\phi$: -120 and 120deg, ΔW: -1.5 and 1.5MeV

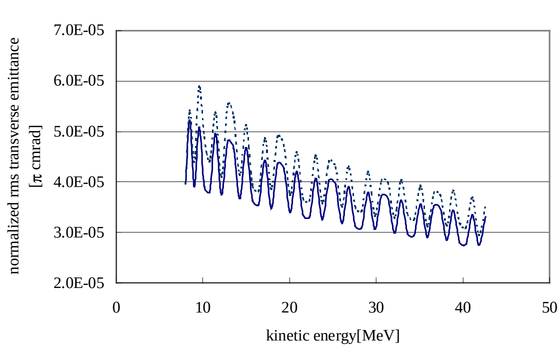

Fig.3 rms emittance along the SC linac
solid line: observed from the beam center.
dotted line:observed from the beam transport axis.

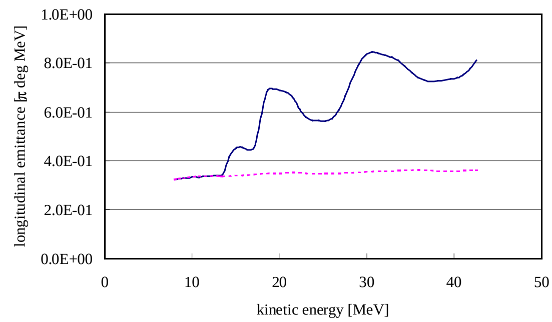

Fig.4 longitudinal emittance along the SC linac
solid line: sc linac with rf missing sections.
dotted line : sc linac without rf missing sections.

On the other hand, it is found that the longitudinal emittance grows considerably as shown by solid line in Fig.4. In order to investigate this phenomenon, a calculation was carried out by introducing the virtual sc cavities to the above rf missing sections. This result is also shown by dotted line in Fig.4. From these results, It is thought that this longitudinal emittance growth is attributed to the arrangement of the cavity rather than by the asymmetrical field. Because $\Delta\phi$ becomes large when particles travel the rf missing sections between the neighbouring cryomodules and finally ΔW spreads out.

5 CONCLUSIONS

The results of beam dynamics calculation by the impulse approximation, in which actual field distribution is used, are as follows;

(1) Though the asymmetrical rf field enlarges the transverse emittance, the beam behaviour is similar to that in the sc linac with the $\lambda/2$ cavities, and also all 10000 particles can pass the linac without loss in the same way as the linac with the $\lambda/2$ cavities.

(2) The sc linac without missing rf sections between the cryomodules is preferable if small longitudinal output emittance is required

(3) For further studies on beam behaviour, it is necessary to take the space charge effect into the code and optimize the cavity shape to decrease E_{max}/E_{acc}.

6 REFERENCES

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