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RFQ FOR HEAVY ION FUSION

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Summary

RFQ is promising as low β linac for heavy ion fusion. The bunching characteristics for $^{238}U^{+1}$ beams have been investigated and the primary results have been shown. There is a possibility of obtaining sufficiently narrow longitudinal emittance and acceleration of several MeV within reasonable distance.

Introduction

The primary advantage of the inertial confinement fusion is that the system can be divided into subsystem namely drivers, reactor construction, pellet and so on. For the last several years, the possibility of inertial fusion using high energy heavy ion beams have been discussed[1] because of the efficient energy deposition to the pellet and the higherr driver efficiency compared to the laser beams.

From the viewpoint of the energy efficiency of power plant, it is necessary to keep the particle loss very small during the beam acceleration. When some accelerator systems for heavy ion fusion, such as RF linac based system, Synchrotron based system and Induction linac based system[2] are considered there is the common serious problem for low velocity region.[3] The beam intensity limitation of linacs often accurs at low velocity because Q magnet focusing is weak. Further it is very important to reduce the particle loss at the matching region between the ion source and the drift tube linac. The high particle capture efficiency and the narrow longitadinal emittance are strongly required for the buncher of the heavy ion fusion accelerator system.

Recently, the performance and application of radiofrequency quadropole structure[4] have been considered for the acceleration of low velocity ions. It is very attractive that RFQ can accomplish the narrow longitudinal emittance suitable to the acceptance of usual drift tube linac with about 100% capture efficiency. This is the very reason why RFQ should be applied to the low velocity region of the accelerator system for heavy ion fusion.

We report preliminary results of RFQ research for heavy ion fusion in this paper. The longitudinal emittance of $^{238}U^{+1}$ beams is computed in some cases, where the initial beam energy is 50KeV and the final energy is 2.5MeV. The operating frequency of RFQ is 40MHz, so that the initial cell length is 2.75mm, which can be reasonably manufactured.

Longitudinal Acceptance of Linac

From a familiar phase oscilation equation, the phase width $\Delta\phi$ and the energy width ΔW for stably accelerated particles can be given by the following equations,

$$\Delta W\ (\mathrm{eV}) = \left(2E_0\ \gamma_s^3 \beta_s^3 \frac{M\ c^2}{e}\ \frac{\phi_s \cos\phi_s - \sin\phi_s}{\pi}\right)^{\frac{1}{2}} \quad (1)$$

$$\frac{\Delta\phi}{\Delta W} = 2\left(\frac{\sin\phi_s - \phi_s \cos\phi_s}{\sin\phi_s}\right)^{-\frac{1}{2}} \quad (2)$$

where E_0 is the average axial electric field and E_0 = 1.0 MV/m in this estimation, c is the light spee, is the wave length, $\beta_s = v_s/c$, v_s is the synchronous particle velocity, $\gamma_s = 1/\sqrt{1-\beta_s^2}$, e is the electric change, M is the ion rest mass, and ϕ is the synchronous hase of the acceleration.

For ϕ_s = -40° and -30°, ΔW, $\Delta\phi$ and logitudinal emittance are given in Table I, where the beam energy is 2.5MeV. Equation (1) shows that to raise the initial energy to linac allows wider acceptance, so that the acceleration in RFQ is also significant. The acceleration length of RFQ can be made less than 10m when the final energy is several MeV. The linac operating frequency is 80MHz, although it is twice the RFQ operating frequency. If the Alvarez linac is used for the following acceleration after RFQ the linac diameter is extremly large at 40MHz operation. Therefore it is tried to construct the linac with higher operating frequency. Because the gap spacing of the initial cell is about 1.4cm for g/L = 0.35, the design is not so troublesome. For the usual synchronous phase ϕ_s = -30°, we obtain the longitudinal acceptance of 100π(rad.keV) with eqs. (1) and (2).

Calculation of Longitudinal Emittance

The axial particle motion is only considered in FRQ axial electric field. The basic equation of motion is expressed by

$$\frac{d^2X}{dt^2} = \frac{e}{M}\ E_z \cos(wt + \phi) \quad (3)$$

where $E_z = E_m \cos(kz)$,
$\phi = -kz + \phi_i + C_1 z$,

k is the wave number of the vane, ϕ_i is the initial phase, c_1 is the phase variation coefficient, z is the particle axial position. the synchronous particle position z_s is given by the next equation,

$$\frac{d^2z_s}{dt^2} = \frac{e}{M}\ E_z \sin(c_1 z_s) \quad (4)$$

E_m and synchronous phase ϕ are slowly changed as shown in Fig.1. There are two cases for ϕ_s variation (c_1 = 10°/m and 20°/m), and for each C_1, E_m is changed in two ways (C_2 = 0.6MV/m/m and 1MV/m/m). The phase difference $\Delta\phi$ is given by

$$\Delta\phi = k\ (Z_s - Z) + \phi_i \quad (5)$$

$$E_m = C_2 Z,$$

where C_2 is the electric field variation coefficient. However E_m has the maximum as shown in Fig 1. which is 2.2MV/m.

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Results

The $\Delta\phi$ - ΔW phase space of the axial particle motion for some C_1(deg./m) and C_2(MV/m/m) as shown in Fig.2 is shown in Fig.2. In Fig.1, the vertical axis is particle energy (in MeV) and the horizontal axis is the phase difference (in rad.) to the synchronous particle. The longitudinal emittances in some cases are shown in Table II. As C_1 and C_2 increase, the length necessary to reach the final particle energy of 2.5 MeV is reduced as shown in Table III, where $D_{2.5}$ is the distance for the final energy of 2.5 MeV, while the longitudinal emittance becomes broader and is about 16π (rad.keV). When C_1 = 10^{o}/m, the capture efficiency is almost unchanged in C_2 = 1.2 MV/m/m and 0.6 MV/m/m. The capature efficiencies are listed in Table IV, where η_c is the capture efficiency. η_c is 99.6% for C_2 = 1.2 MV/m/m and 99.5% for 0.6 MV/m/m, while it is less than 99% in all cases for C_1 = 20 deg./m. The acceleration length of RFQ for C_1 = 10 deg./m is 5 $\sim$ 6m for all cases of C_2. In the same C_2, the acceleration distance for C_1 = 20 deg./m is about 1m shorter than that for C_1 = 10 deg./m.

From the viewpoint that it is the primary factor to transfer the particles as much as possible within the acceptance of the drift tube linac at the next stage, C_1 = 10 deg./m and C_2 = 0.6 MV/m/m are considered to be most suitable. The longitudinal emittance for this condition is 12 π (rad.keV) and is sufficiently narrower than the supposed acceptance as shown in Table I. It is considered, therefore, that even if the operating frequency of linac is two times the operating frequency of RFQ, the beams bunched in RFQ can be accelarated at small particle loss.

Conclusion

As a result of the above calculation, it has been shown that the RFQ, while maintaining quite excellent longitudinal emittance at reasenable acceleration length, can obtain the low velocity acceleration of heavy ions.

In the acceleration system for heavy ion fusion, the use of RFQ is considered to be essential.

As the next stage, investigation has been performed regarding the present lunching slate considering the space charge effect.

Reference

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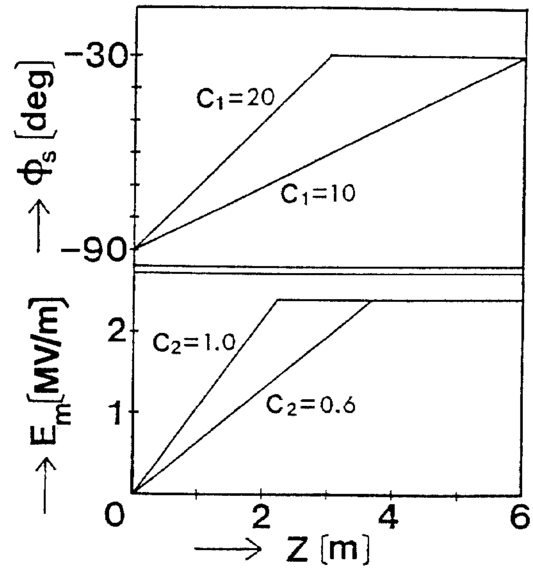

Fig.1 Variation of E_m and Φ_s

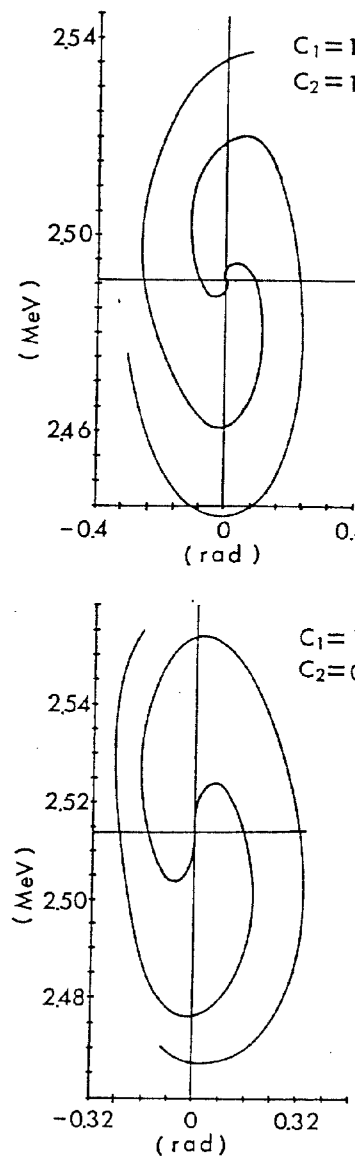

Fig.2 ΔW-$\Delta\Phi$ diagram

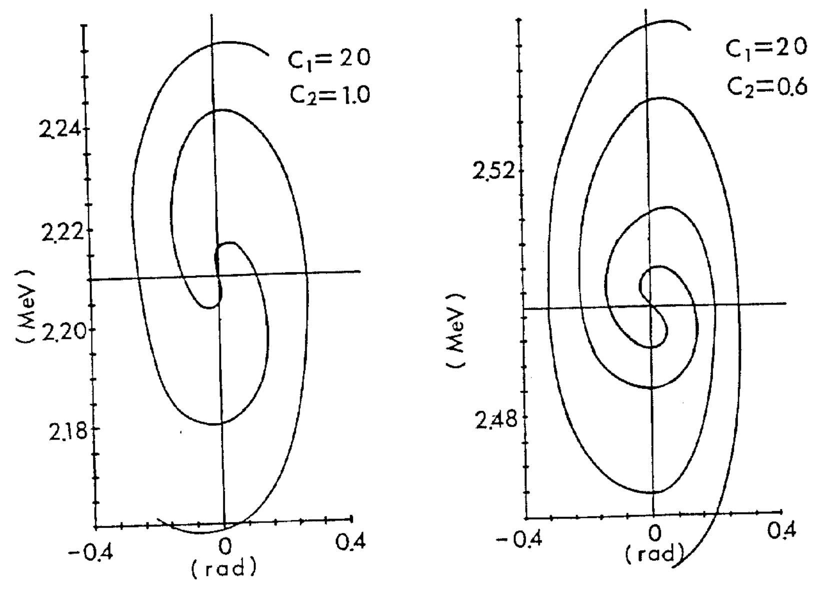

Fig.2 ΔW-ΔΦ diagram

Φ_s (deg.)	-40	-30
ΔΦ (rad.)	0.83	0.61
ΔW (keV)	260	170
Acceptance (rad·keV)	220π	100π

Table I. Longitudinal acceptance of linac

	Emittance (rad·keV)	
C_1	C_2 (MV/m/m)	
(deg./m)	0.6	1.0
10	12 π	14 π
20	14 π	16 π

Table II. Longitudinal emittance

	$D_{2.5}$ (m)	
C_2	C_1 (deg./m)	
(MV/m/m)	10	2.0
0.4	6.3	5.6
0.6	5.9	4.9
0.8	5.5	4.4
1.0	5.4	4.2
1.2	5.3	4.1

Table III. Acceleration distance for 2.5MeV

	η_c (%)	
C_2	C_1 (deg./m)	
(MV/m/m)	10	20
0.4	99.3	98.3
0.6	99.5	98.8
0.8	99.5	99.0
1.0	99.6	99.0
1.2	99.6	99.0

Table IV. Capture efficiency