WORK ON RF QUADRUPOLE FOCUSING STRUCTURES AT GSI

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Summary

Layouts have been made for a linac accelerating heavy ions ($^{238}U^{1+}$, 40 m long, or $^{238}U^{2+}$, 18 m long) from low energies up to 0.1 MeV/u, designed for high intensities and working at low duty cycle. At this energy the beam is to be stripped and transferred to the UNILAC, replacing the low brilliance ion sources for the planned synchrotron filling regime. Because of the need for very strong focusing, the linac must have rf quadrupole focusing which is similar in principle, but of different technical shape from those of Kapchinski - Teplyakov and the Los Alamos approaches. Also the rf cavity design is different. The frequency is typically low, around 10 MHz or lower. The linac will have the property of adiabatic bunching. This is a good condition for transporting beams of more than 10 mA, or even 1 ampere.

Introduction

Rf quadrupole (RFQ) linac structures have been recognized to be probably the most powerful structure for very slow ion beams ($\beta < 1$ %) of high intensity. At GSI, Darmstadt, two applications have triggered development work: (1) the high-intensity mode of the heavy ion synchrotron (SIS) demands for a bright U^{1+} or U^{2+} beam; (2) the structure is a promising candidate for the first section of a heavy ion ignited fusion (HIF) accelerator, the design of which is aided if it is able to transport and accelerate currents of 1 ampere or more of Cs^{1+} or Bi^{1+} ions. In this case the micro-bunch frequency, or the frequency of the first linac stage, must be low (2 or 4 MHz),but even this frequency is an inherent advantage to the scenario.

Electrode Structure

The merits of the RFQ structure originally described by Kapchinskij and Teplyakov can be reviewed as follows: at velocities $\beta < 1$%, electric quadrupoles are more powerful than magnetic ones. Generally, rf voltages and fields of high amplitudes can be generated and handled easier than electrostatic fields because of the absence of solid insulators , and because of higher sparking limits in the vacuum. Since the focusing period is as short as possible,($\beta\lambda$), and the lenses are as strong as possible, RFQ channels have a high stability, a high acceptance at modest aperture, and a high current holding ability.

A homogeneous RFQ channel of aperture radius R, with a voltage U of wavelength λ applied to the electrodes, has a focusing phase σ per $\beta\lambda$ cell, or "focusing frequency" :

$$\sigma_{oo} = \frac{1}{\sqrt{8}\,\pi} \left(\frac{q}{A}\right)_{ion} \frac{U}{932\ \text{MV}} \cdot \left(\frac{\lambda}{R}\right)^2 \qquad (1)$$

By shaping the electrodes longitudinally,one can generate an accelerating field distribution with a potential distribution on the axis:

$$\Phi = \frac{U}{2}\,(1 + A_1 \cos(kz) + \text{higher harmonics}) \qquad (2)$$

with $k = 2\pi/(\beta\lambda)$. The amplitude A_1 can be interpreted as the transit time factor T,of drift tube structures:

$$T = (\pi/4)\cdot A_1 \qquad (3)$$

By shaping the electrodes and keeping a clear aperture of 2 R, the quadrupole strength is weakened, so that the focusing frequency σ_r becomes smaller than the focusing frequency of the homogeneous channel, σ_{oo}. It again becomes smaller due to the well-known acceleration defocusing term, by a factor f, which depends on details of the geometry, the particle phase ϕ, and on σ_{oo}:

$$\sigma_r = \sigma_{oo}\cdot f\ (\text{geometry},\ \phi,\ \sigma_{oo}) \qquad (4)$$

The general form of f is :

$$f = \sqrt{a + b\cdot\cos^2\phi + \sqrt{2}\pi^3 (R/\beta\lambda)^2\cdot(A_1/\sigma_{oo})\cdot\sin\phi} \qquad (5)$$

where a and b are functions of only the geometry. There is an "orthodox" layout of RFQ structures which keeps the quadrupole strength constant along z, and simultaneously avoids higher harmonics than the fundamental in Φ (eq.(2)), so that b = 0, and the transverse motion has the least possible coupling with the phase motion. It would be wise to apply this orthodox shaping at least in the very first few meters of a structure, especially when adiabatic bunching is applied. But in order to design an economical structure, with appreciable transit time factors of more than a few percent, it is more pragmatic to allow for b > 0. To enhance the transit time factor T, or A_1,a "drift-tube with long quadrupoles" was designed, as shown in Fig. 1. This also has advantages for the type of rf cavities described later. The calculating procedures for finding the values of the coefficients a and b are nearly as easy as in the case of the orthodox structure[3].

Figures 2,3, and 4 show the parameters for a U^{1+} layout, with R = 1.2 cm, U = 200 kV, f = 9 MHz, and σ_{oo} = 0.765. The structure for β_i = 0.15% to β_e = 1.5% will be 40 m long, and capable of transporting a 25 mA beam current. A similar 18 m long structure for U^{2+} at 13.5 MHz will transport 35 mA. The currents have been estimated from the formulae for transverse stability. Looking at the bunch shape (Fig. 4),there is a high level of confidence that longitudinal instabilities will play a minor role. The long "cigar" shape of the bunches is a consequence of the adiabatic bunching used in this design. The stable phase ϕ_s (Fig. 3) is shifted gradually from -75° to -30°. The growing stable area condition necessary for the adiabatic bunching procedure is fulfilled when β grows linearly with z. The capture efficiency in this design is 70 %. A few more details are available from a GSI report[4].

Frequency Considerations

Looking at the scaling laws, with the electric field strengths kept invariant at about 15 MV/m, one finds that the transportable current is a function of the wavelengths squared:

$$I \approx 8\ \text{amp}\cdot(q/A)_{ion}\cdot\beta\cdot(\lambda/m)^2 \qquad (6)$$

This means that for q/A = 1/133 (Cs^{1+}), β_i = 0.3%, the frequency must not be higher than 4 MHz if a current of 1 ampere is required. The aperature of this structure must be large, $2R \simeq 10$ cm, and the system voltage $U \simeq 720$ kV, to avoid σ_r values greater than $\pi/2$. Typically one has to deal with very low frequencies.

Rf Cavity Design

It is obvious that in the heavy ion situation as discussed before, the cavity types used in the proton case (Los Alamos: Clover-leaf type[2], and Teplyakov: Split-ring type[1]) are not adequate. Even usual Wideröe stub-line cavities (GSI type) would become too bulky for frequencies below 10 MHz. Studies were made of ways to arrange the inductive stub-line of the Wideröe structure in the longitudinal direction, and to design a TM mode cavity. The design is quite successful, resulting in a cavity of excellent properties (see Fig. 5).

The capacitive currents caused by feeding the acceleration electrodes with a constant voltage, U, are gathered on two pairs of spear-shaped collectors. The shape of the collectors is such that the current density on their surfaces is uniform. In this way an essentially ring-shaped magnetic field is produced, and the power dissipation is minimized. The total magnetic flux around the collector assembly will induce the voltage U. The shape of the collectors has still another good effect: the net electric field flowing to the outer conductor (e.g. in a TEM cavity) is approximately eliminated; therefore, the voltage distribution along the cavity is of an excellent flatness.

The most important effect is that the size of a cavity cell is reasonable even at low frequencies. For instance, the length ℓ is 1/15 of the wave-length, if $r_a/r_i \simeq 3$ and $C' \simeq 30\ \varepsilon_o$. Nevertheless, the R_p value is high (some 100 kohms) and also the shunt impedance is high. Because quotation of shunt impedances will lead to misunderstandings for an adiabatically bunching cavity, it is more meaningful to state that the power loss in the structure is of the order of the power taken by the beam at its current limit, or even much less for the 1 ampere accelerator, because of its low frequency.

The problem of the possible energy step at the entrance of the system arising from the structure asymmetry with respect to ground potential, (while the longitudinal magnetic field structures in use so far are symmetric), can be solved by proper shaping of the first $\beta\lambda$-cell. To avoid repetition of this problem, one should tightly couple together a larger number of cavity cells into a long super-cavity fed by a common power amplifier, or a set of synchronous amplifiers. Thus a continuous bed for the drift tubes is prepared.

Planned Model Work

In cooperation with the group of H. Klein, University of Frankfurt, we plan to build a scaled model (1:4) for protons. The σ values along the accelertor will be identical with those planned for a heavy ion accelerator. The voltages, powers and currents will be moderate, but the model will allow study of all the instabilities which also would occur in a large accelerator.

References

1 I.M. Kapchinskij, V.A. Teplyakov. Pribori i Tekh. Eksp. No. 2 (1970), 19-22.

2 J.M. Potter et al.,"RFQ Accelerating structure Research at Los Alamos", IEEE Trans. NS-26 (1979), 3745-7.

3 R.H. Stokes et al.,"RFQ Beam Dynamics", IEEE Trans. NS-26 (1979), 3469-71.

4 R.W. Müller,"Layout of a High-Intensity Linac for Very Heavy Ions with RFQ Focusing",GSI report 79-7 (1979).

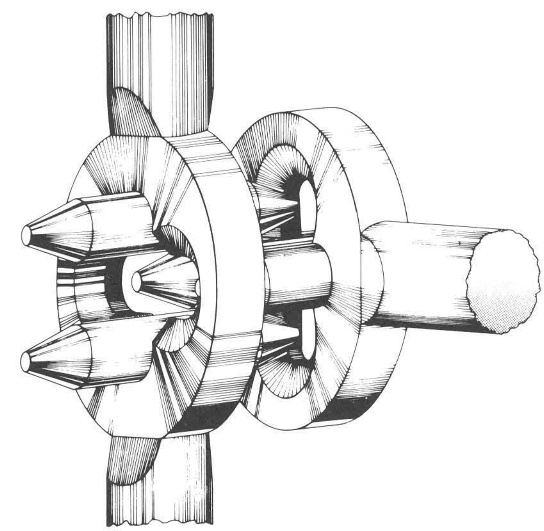

Fig. 1. Drift tube with quadrupole fingers.

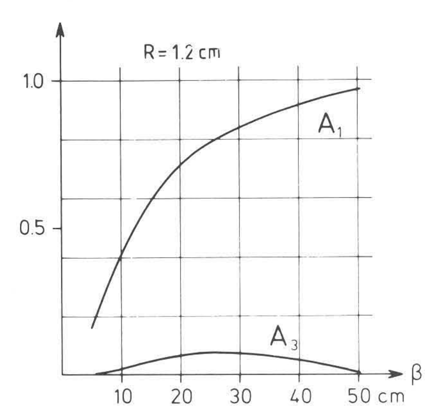

Fig. 2. Potential amplitudes vs $\beta\lambda$

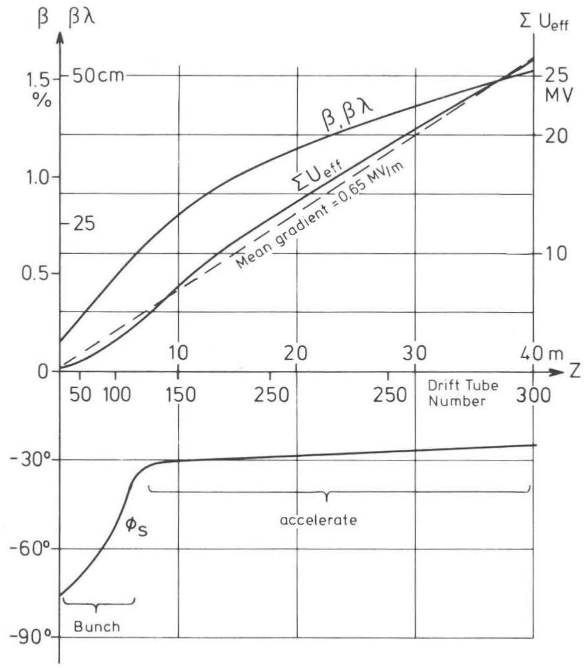

Fig. 3. Beta and phase profile of a 9-MHz layout. In the adiabatic bunching region β grows linearly with z.

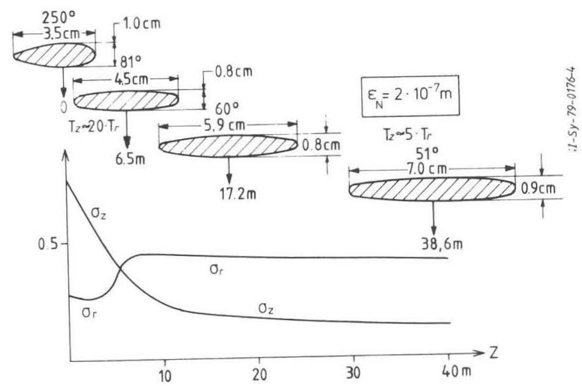

Fig. 4. Radial and longitudinal phase advances ("focusing frequencies"), and bunch shapes. T_r and T_z are the temperatures, T_z is decreasing because of adiabatic expansion.

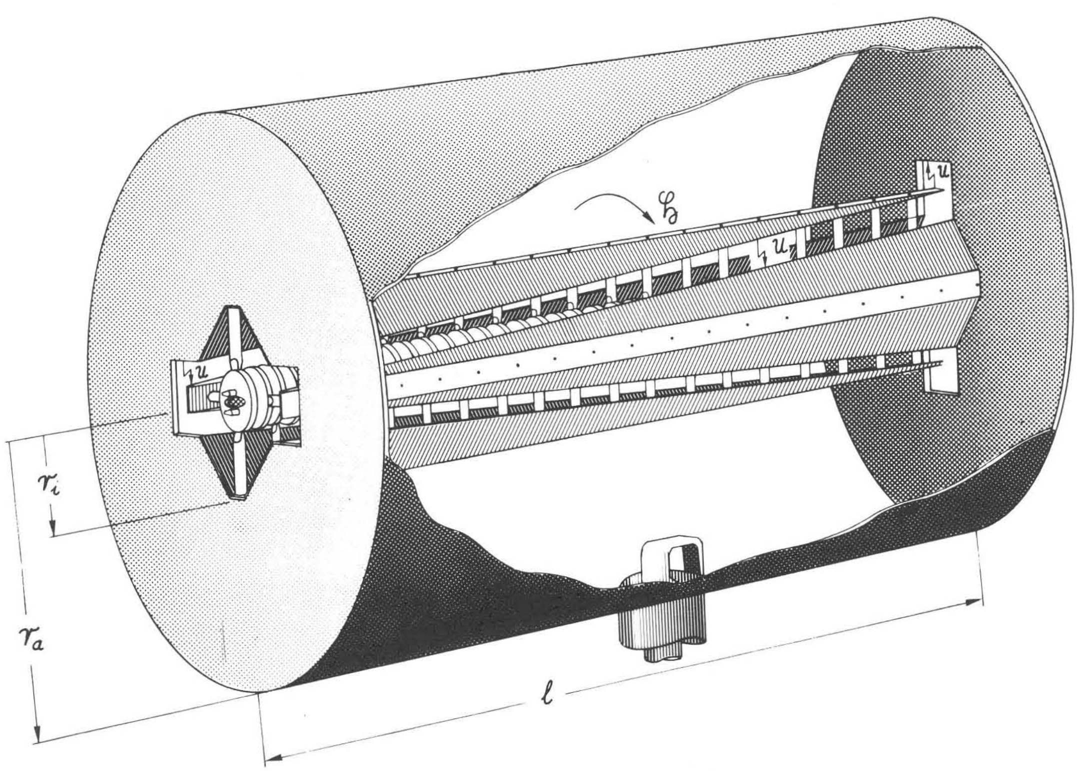

Fig. 5. Rf Cavity

Discussion

Meads, Brobeck: It looks like a very complicated structure to try to align. I wonder what you'd estimate would be the tolerances in lateral positioning of those pieces compared to the radius.

(Editor's Note: The following discussion appears to refer to Fig. 5.)

Müller: The structure is not difficult to align. Perhaps, if you could show the last slide again, I can show you how to align it. First, if you assemble one set of electrodes together with the current collectors, you will be able to align it. Now, the problem which you mentioned is how to align these parts together. Now, this one has a turning point on the other end. You can tilt it there and so you can get it well aligned.

Meads: I guess I was more concerned about the posts that are near the center, in the perpendicular plane; those extensions that come out of each piece - longitudinally, inside there.

Müller: You mean these? They are the entrance to the whole structure, which we use as a short matching region before it. But, in general, I think that adjusting this structure is no more critical than adjusting a drift tube linac.

Meads: I guess I misunderstood, I thought those pieces went all the way down through the structure, and that each of those sections had two of those.

Müller: There are two different types of shaping; that one you mentioned, and one looking more like four vanes near the axis. In both cases, since you can see each electrode, by looking through the structure, you will also be able to adjust it. I don't see any difficulties.