AN ALTERNATIVE APPROACH TO LOW FREQUENCY RF ACCELERATORS AND POWER SOURCES

Yongxiang Zhao
Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

The Muon Collider and Neutrino Factory projects[1] require low frequency rf cavities because the size and emittance of the muon beam is much larger than is usual for electron or proton beams. The range of 30 MHz to 200 MHz is of special interest. However, the size of an accelerator with low frequency will be impractically large if it is simply scaled up from usual designs. In addition, to get very high peak power in this range is difficult. Presented in this paper is an alternative structure that employs a quasi-lumped inductance that can significantly reduce the transverse size while keeping high gradient. Also addressed is a power compression scheme with a thyratron. This gives a possible solution to provide very high peak power.

1 INTRODUCTION

The Muon Collider and Neutrino Factory projects have gained worldwide interest. The size and emittance of its muon beam is much larger than that for typical electron or proton accelerators. For example, the beam size at the front end is considered to be 60 cm in diameter. The large size requires the rf system to be at low frequency (LF). At the phase rotation and early cooling stages the frequency is in the range of 30 to 200 MHz. However, to achieve a high gradient with LF is a big challenge; the lower the frequency, the more difficult it is. To obtain very high peak power at LF also is difficult. This paper is intended to address a new approach that will be particularly valuable for low frequency applications, say at 30 MHz.

2 RING-BAR STRUCTURE [2]

The frequency of most high gradient linac accelerators is in or above the L-band, and the gradient of most LF accelerators is moderate or low. Usually a LF cavities has a narrow gap for increasing the capacitance and/or a quarter wavelength short-circuit line to add inductance. The accelerating gap occupies only a small part of the longitudinal length, which limits the average gradient. On the other hand, if one scales up a high gradient cavity to low frequency, the transverse size will be unreasonably large.

To lower the frequency one must increase the capacitance or inductance. The accelerating region, which is normally on the axis of the cavity and has a high electric field, is a capacitive region. The outer part of the cavity is an inductive region.

In order to increase the inductance, one may enlarge the volume or employ a folding line. Many possible shapes have been studied. However, for a 30 MHz cavity, the diameter becomes too large, say about 3 meters or more.

In short-wave transmitters (<30 MHz), the resonator is usually composed of lumped elements -- capacitor and coil. The inductance of a coil or a wire is much larger than that in a typical cavity. One may consider if a coil or wire can be employed in a cavity.

Fig. 1 shows a ring-bar structure. An array of rings is placed along the axis. Each ring has a bar connecting to the envelope, which is the ground. The rings provide the capacitance, while each bar provides some inductance. As is well known, the thinner the wire, the larger its inductance. In principle, one may get a very large inductance. However, engineering considerations require a minimum thickness, and some trade-offs are needed.

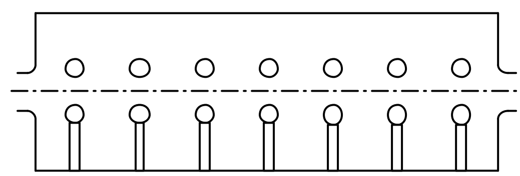

Fig.1 The ring-bar structure.

The structure is somewhat like a drift-tube linac (DTL). However, a DTL is applicable only for a beam of low β and the bar does not function as a lumped inductance.

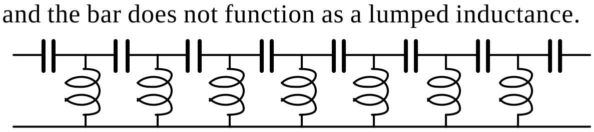

Fig.2 The equivalent circuit

Fig. 2 shows the equivalent circuit for the ring-bar structure. Obviously, it is a high-pass filter circuit or a travelling wave structure.

3 TRAVELLING-WAVE CAVITY

Travelling-wave structures have been widely applied in linacs. However, a travelling-wave accelerator requires a very large power supply. This is especially difficult at low frequency. For the above-mentioned structure there is another special concern: travelling-wave structure must have both ends matched with the wave impedance. That requires matched input and output couplers with strong coupling. For a high frequency such as S-band the technology is mature. But this is a challenge for the LF structure in question, where the transverse dimension is much less than a wavelength.

To overcome the above problems, one can make a standing wave cavity by shorting both ends as sketched in

Fig. 1. However, it will weaken the beam interaction, as is measured by the "transit time factor". A standing wave can be regarded as a superposition of a forward wave and a backward wave. Only the forward wave can be synchronized with the beam; the backward wave has little interaction with the beam.

Fig. 3 shows different field patterns (E_z-z) in the interaction gap. Fig. 4 shows the corresponding transit time factors versus transit angle, which is defined as $\theta = 2\pi t/T$, where t is the time required for a particle to cross the accelerating gap, and T is the period of the rf field.

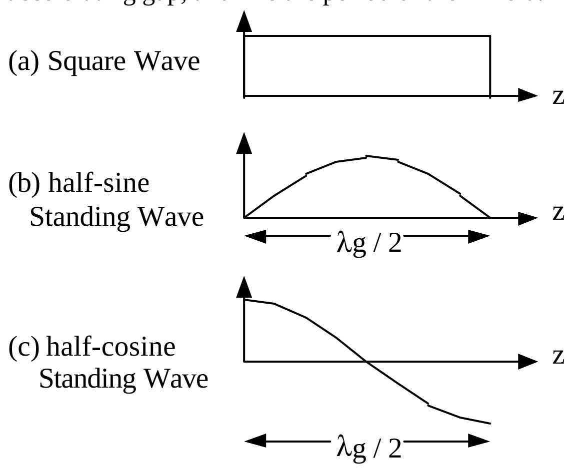

Fig.3 The field distribution in the interaction gap

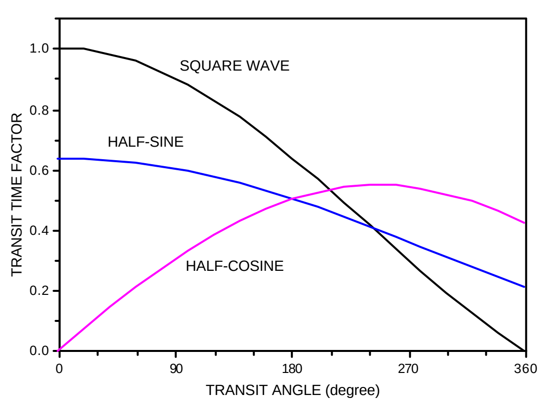

Fig. 4 The transit time factor of different field pattern

It should be noted that in the ring-bar structure the longitudinal field E_z must have the cosine pattern as shown in Fig. 3(c). This is because the metal wall on both ends can only short the transverse field E_t, whereas E_z is perpendicular to the wall. Therefore, at both ends $E_t = 0$, corresponding to a sine pattern as in Fig. 3 (b), E_z is a cosine pattern. Simulations also have confirmed this argument.

If the transit angle is π (= 180^{o}), from Fig. 4 the transit time factor of the half-cosine pattern is 0.5, because in the middle part the interaction is weak due to the node. It seems bad. However, for most LF cavities, the accelerating gap occupies only a small part of the longitudinal length, while for a cavity like Fig. 1 the gap occupies the entire length, though the central part isn't effective. So if the maximum field strength stays the same, the average gradient can be much larger than usual. This is the major advantage of this kind of structure.

4 SIMULATION

Some particular shapes and sizes have been simulated using the code MAFIA, focusing on the low frequency range[2].

Fig. 5 shows the cross section of a special structure shaped like a wheel spoke, where the bar has been lengthened to increase its inductance. We chose four bars, to achieve better support. They also form cooling channels.

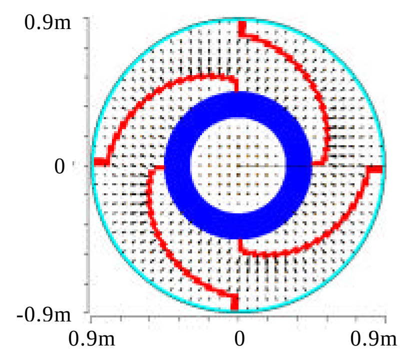

Fig. 5 The cross section of a ring-bar and the field

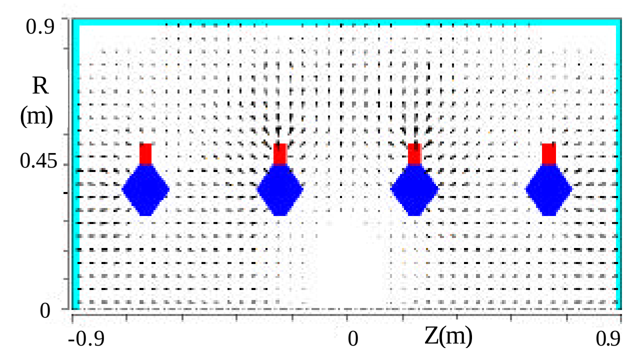

Fig. 6 The field pattern in r-z cross section

From Fig. 6 one can see that, as expected in the central part, the field E_z at the axis is near zero. Meanwhile E_t reaches its maximum. The maximum transverse field may be larger than the longitudinal field. Considering that there is a longitudinal focusing magnetic field in the muon project, the effect of magnetic isolation may alleviate the risk of breakdown

The $E_z(z)$ on the axis is shown in Fig. 7. The parameters of this particular cavity are:

Aperture	0.6 m
Cavity length	1.8 m
Number of sections	4
Cavity diameter	1.8 m
Frequency	60.5 MHz
Unit length R/Q	82 ohm/m
Q	26000
Impedance	3.95 Mohm
Unit length impedance	2.15 Mohm/m

The above example has not been optimized. The beam velocity may affect the data, but not critically. For different frequencies the cavity length or the number of sections should be changed correspondingly. Lengthening and deforming the bar to form a spiral can significantly increase the inductance. It can bring down the frequency to 30 MHz or lower without increasing the transverse dimensions. Unfortunately, MAFIA couldn't give a precise result for this case due to the complexity of the shape. Thus one has to rely on experiment or a more powerful code, if available.

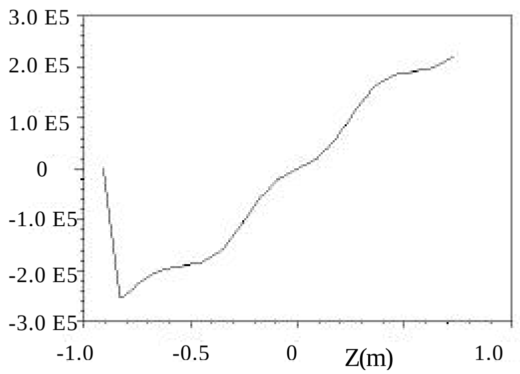

Fig.7 The electric field E_z along axis

Usually, a lumped device such as a coil can not achieve a very high Q. The Q value of 26000 listed above is not bad. But, one may question the precision of the result from MAFIA. Surely this is a topic requiring further studies. However, one advantage of this kind of structure is that the capacitance is very low in comparison with other LF cavities. This means, to get a given accelerating voltage, one needs less energy to fill it. This is important for short pulse operation. A muon collider is just such a case.

Another concern is the required power. Although the mentioned structure has the potential to get a relatively high average gradient, and consequently one has to supply a huge LF peak power. This is difficult at present. The next section proposes an alternative power source.

5 A LF POWER SOURCE SCHEME

Fig. 8 shows the principle of a compression scheme using energy storage and a unique switch.[3] To charge the storage cavity, one might employ a CW tetrode (power source marked as PS in Fig. 8). The output of the storage cavity is connected to a half-wavelength cable with a switch at the other end and a load at the midpoint. When the switch is open, as shown in Fig. 8 (a), the load branch is at the node of the voltage. Therefore no power goes to the load, and the storage cavity sees an open circuit, which means little power leakage. When the switch is closed as in Fig. 8 (b), the right quarter-wavelength cable acts as an open circuit. The storage cavity then connects directly to the load (e.g., the accelerator cavity), to which the energy drains.

The energy storage is a superconducting cavity (S.C. in Fig. 8) so it has little loss during the long charging time. This makes it possible to use a moderate power tetrode.

The switch is a key component. A thyratron is considered suitable. Although thyratrons are usually used in modulators or video switches, they may also be applicable at LF. The switch should hold off a voltage V without breakdown when the switch is open, and should carry a current $I = V/Z_0$ when closed. There are many thyratrons on the market with enough power to satisfy these requirements.

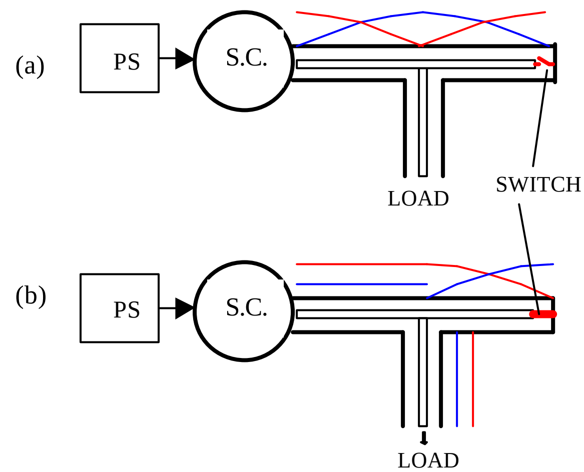

Fig.8 Principle set-up of storage – switch compression scheme.

A special apparatus would need to be designed to hold the thyratron inside a rigid cable. In addition, a special bias current circuit would need to be provided to guarantee that the current is always positive as required by a normal thyratron.

This scheme has the potential to supply large peak powers. The major restriction is breakdown inside the cable. Since the cable is a low impedance device, the voltage can be in the tens of kilovolts range and should not be a big problem.

6 ACKNOWLEDGEMENT

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7 REFERENCES

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