CONF-791022--2

LA-UR-80-342

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SUBMITTED TO: Proceedings of Heavy Ion Fusion Accelerator Study, October 29 - November 9, 1979, Berkeley, CA

MASTER

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Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

RF LINAC APPROACH TO HEAVY ION FUSION*

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ABSTRACT

The necessary properties of "funneling" particle beams from multiple accelerators into combined beams having higher current are outlined, and methods are proposed which maximize the efficiency of this process. A heavy ion fusion driver system example is presented which shows the large advantages in system efficiency to be gained by proper funneling.

The rf linac, when operated at sufficiently high currents of singly-charged heavy ions in the range of 1 to 10 GeV at frequencies in the range of 100 to 400 MHz, is an efficient accelerator, where most of the power is transferred to the beam. Under these conditions, the total rf power required to accelerate a given particle to a given particle energy is essentially independent of the charge state; thus if the singly charged heavy ion, with its low charge-to-mass ratio, is the preferred particle for reasons associated with other parts of the facility, it is quite acceptable from the rf linac point of view. Furthermore, the relatively high current reduces the required linac pulse length, causing the optimum acceleration gradient to be higher** and the optimum accelerator length to be shorter than would be the case for lower currents of similar ions.

Filling such machines, on the other hand, is a major problem, requiring a multiplicity of low-frequency linacs at the lowest energy with relatively low

*Work performed under the auspices of the U. S. Department of Energy.

**In low duty applications, where the rf power sources are peak power limited, the power-related costs are proportional to the peak power and the optimum acceleration gradient is independent of the beam current. In fixed high duty applications, where the rf power sources are average power limited, the power related costs are proportional to the average power, which is also proportional to the peak power, and the optimum accelerator gradient is independent of the beam current. In fixed average current applications, the duty factor is inversely proportional to the peak beam current, and in those cases which are average power limited, the optimum acceleration gradient is proportional to the square root of the peak beam current.

currents, followed by smaller numbers of linacs at higher energies with higher frequencies and currents, culminating in a single linac at the highest frequency and current for the major portion of the facility.

Let us define "funneling" as the interlaced filling of one linac of frequency Nf from N linacs of frequency f. For a number of reasons, the most interesting value of N is 2. For N = 2, funneling implies a doubling of the frequency whenever the space charge limits of the structure permit and a combination of the beams from two linacs at the old frequency into each linac at the new frequency. In principle, it is possible to accomplish the funneling with no increase in the transverse phase space and a simple addition of the longitudinal phases from the two linacs using an rf deflector.

Funneling is an important concept. It implies the filling of every bucket at each new frequency, thereby realizing the full space charge capabilities of each portion of the linac. It maximizes the frequency and consequently minimizes the size and power consumption of each portion of the structure. Empty buckets represent a valuable resource that must not be wasted. They represent prime space in which additional beam can be accelerated with no additional hardware, real estate, or pulse length, and with only the additional power required for the additional beam. The additional beam current serves to reduce the linac pulse length and to reduce the severe requirements on the final bunching system involving multiple accumulator rings and linear induction bunchers.

The concept of funneling was invented at the 1977 Heavy Ion Fusion Workshop. Since then, neither the ANL nor BNL designs have fully exploited this concept, having only one eighth to one-twelfth of the buckets filled, and particle currents that are factors of 10 to 100 below what they could be. This causes the pulse lengths to be longer, the optimum gradients to be lower, and the linac lengths to be longer in those designs than in the designs which fully exploit funneling.

Strict funneling implies a constant ratio between the beam current and the frequency of each portion of the linac. The relative difficulty of funneling depends on the ratio of the physical separation of the beams to their particle wavelength ($\beta\lambda$). The larger this ratio, the more difficult the funneling. At the lowest betas, it is attractive to consider arrays of linac channels within a common linac structure, where the beam to beam spacings can be quite small.

The radio frequency quadrupole (RFQ) linac structure promises to be the best low beta linac structure, offering high capture of very low energy beams and acceleration with a minimal emittance growth.* Furthermore, the RFQ lends itself to array-like configurations as shown in Fig. 1, which can be driven by external resonant circuits in the same manner as Wideröe linacs. By staggering the geometrical modulations that produce the accelerating voltages, the beams can be made to interlace as required by funneling, without the necessity for introducing varying lengths into the funneling transport lines.

Candidates for the second linac structure in the system are an RFQ linac, an electrostatically-focused π, 3π Wideröe linac, and a magnetically-focused π, 3π Wideröe linac. At a few MeV, the electrostatically-focused π, 3π Wideröe linac seems to be the best choice, because the RFQ efficiency is dropping, while the required magnet strengths are still impractical.

If the original array of RFQ linacs involves more than two interlaced beam channels, the second structure must also accommodate an array of more than one interlaced channel. It should be noted that multiple-holed drift tubes in a Wideröe or Alvarez configuration do not satisfy the interlaced requirements of funneling. Figure 2 suggests the basic features of a double-barreled, electrostatically-focused π, 3π Wideröe linac which does satisfy this requirement and would seem to have some attractive rf and mechanical properties. This idea could be extended to a larger number of beams at the cost of further complication.

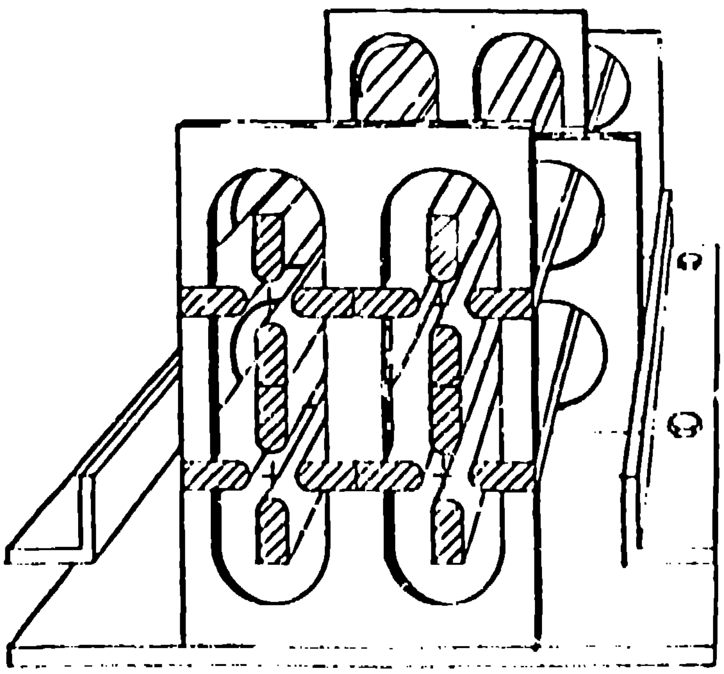

Fig. 1.
Array of Four RFQ Channels

A multiple channel, magnetically-focused π, 3π Wideröe linac could be based on the same idea, where the magnetic quadrupoles could have an outer diameter equal to the channel separation (not an undue constraint). In this case, it would seem preferable to limit the vacuum to the rf accelerating regions and the interior of a beam

*It is the best transition that we know of between a dc injector and an rf linac.

tube passing through the magnetic quadrupoles. This would leave the magnetic quadrupoles completely exposed on top of the structure to facilitate alignment and services.

We realize that requirements on brightness have a strong influence on how close we can operate to the space charge limit. However, the important properties of funneling and the impact outlined above on structure selection are equally valid for lower currents. We are proceeding with more detailed design of a facility configuration using these ideas; in the following paragraphs, we outline a preliminary, idealized configuration which illustrates the potential advantages of full funneling.

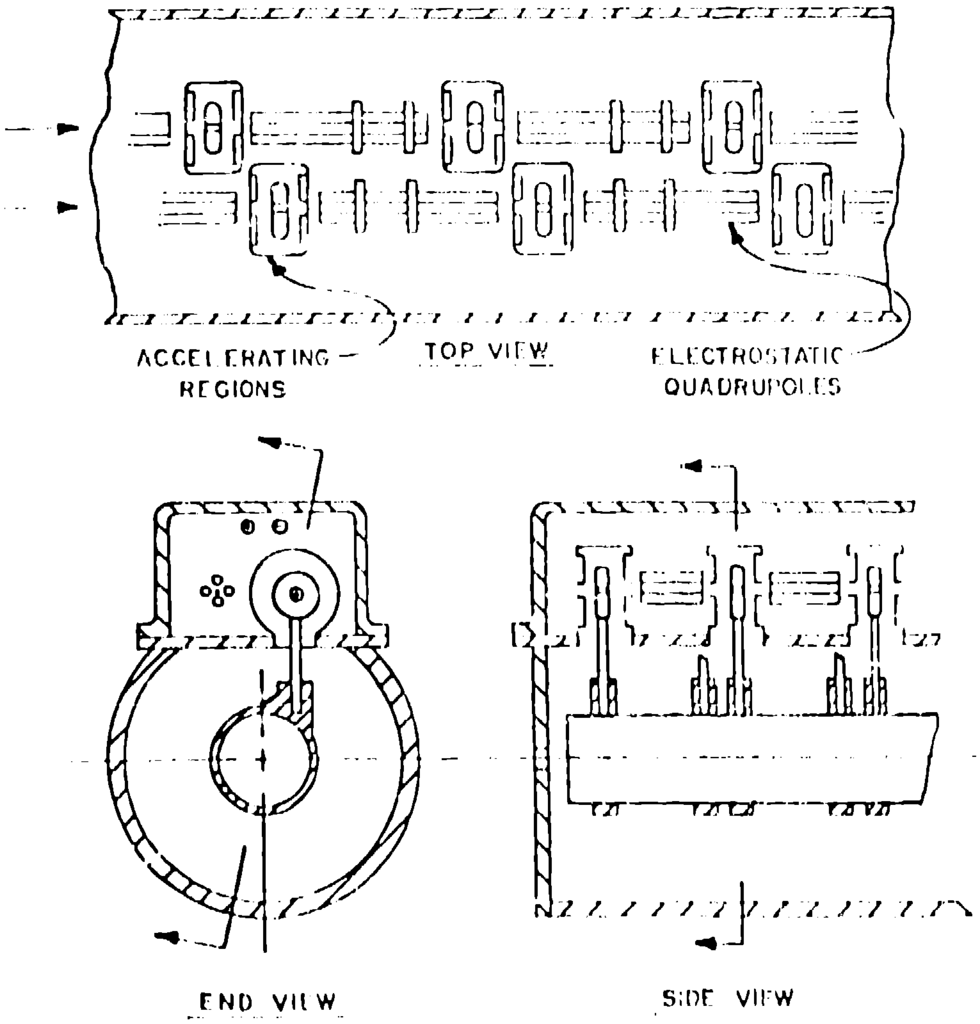

Fig. 2.
Double-barreled, electrostatically focused, π, 3π Wideröe linac.

end. Detailed studies of the beam dynamics in these structures have not been made, nor have studies been made of the problems associated with funneling.

The transition energies in Table I are based on a ratio of the space charge force to the focusing force of 0.5, which corresponds to an allowed tune depression of about 30%.[1] Within the RFQ, this limit is evaluated at the end of a bunching subsection. For all other cases, these limits apply at the input or transition energy to each new structure. If we decide, because of emittance growth or current loss, to operate further from the space charge limit, we can delay the transitions to somewhat higher energies where the limiting currents are higher.

The total length of the linac is only 3.4 km, which is quite short compared to previous designs. This is the result of the relatively high acceleration gradients in the latter portions of the facility, namely, 1.5 MeV/m at 100 MHz, 2.0 MeV/m at 200 MHz, and 4.0 MeV/m at 400 MHz. These gradients at these frequencies are known to be technically feasible, and they can be shown to be economically attractive because of the high frequencies and high peak beam currents that result from funneling.

In our present stage of thinking, we would propose to configure the 32 channels of the first structure as eight independent arrays of four channels as shown in Fig. 1, the 16 channels of the second structure as eight independent double-barreled structures as shown in Fig. 2, and the 8 channels of the third structure as 8 conventional 50 MHz Wideröe structures. As such, the early stages of the facility, those with the highest multiplicities, would take the form of eight identical assemblies, each accommodating a total current of 100 mA. This configuration lends itself to the possibility of developing, prototyping and testing one-eighth of the total configuration in a staged development of the total facility.

ACKNOWLEDGMENTS

The author wishes to acknowledge many useful discussions on these topics with his colleagues, R. H. Stokes, T. P. Wangler, K. R. Crandall, and R. A. Jameson.

REFERENCE

1. "Space Charge Limits in Linacs," T. P. Wangler, to be published.

We believe that the space-charge limit for Xe^{+1} in a magnetically-focused rf linac is approximately one ampere at 1 GeV and 100 MHz, based on a uniformly-filled, three-dimensional ellipsoidal model and a smooth approximation of the transverse focusing forces.[1] This limit increases with energy and decreases with frequency, such that at 3 GeV and 400 MHz the limit is also approximately one ampere. Thus for the major portion of a 10 GeV heavy ion fusion facility based on the rf linac approach, one can accommodate currents in the order of an ampere at frequencies as high as 400 MHz. If one shoots for 800 mA at 400 MHz in the major portion of the facility, one is obliged to start out with 32 linac channels, each carrying 25 mA at 12.5 MHz followed by five stages of funneling.

A schedule of linac structures which, if combined through funneling, would produce an 800 mA beam of Xe^{+1} at 10 GeV is given in Table I. Each structure, after the initial RFQ section, is close to its space charge limit at the low energy end and significantly below its space charge limit at the high energy

TABLE I

SCHEDULE OF LINAC STRUCTURES

Structure	1	2	3	4	5	6
Type	RFQ	EFW	MFW	MFA	MFA	MFA
Number	32	16	8	4	2	1
Current (mA)	25	50	100	200	400	800
Frequency (MHz)	12.5	25	50	100	200	400
Energy in (MeV)	0.2	6	28	190	750	3000
Beta in	0.002	0.010	0.021	0.056	0.110	0.217
Beta*Lambda (m)	0.043	0.118	0.128	0.166	0.165	0.163
Energy out (MeV)	6	28	190	750	3000	10000
Length (m)	21	26	125	373	1125	1750
Total length (m)						3420

RFQ = Radio frequency quadrupole linac.
EFW = Electrostatically-focused Wideröe linac.
MFW = Magnetically-focused Wideröe linac.
MFA = Magnetically focused Alvarez linac.