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SUPERCONDUCTING RFQ'S IN THE 100 MeV RANGE

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Superconducting technology may open the door on the radio frequency quadrupole (RFQ) parameter space to yield interesting proton RFQ's to energies as high as 100 MeV and heavy-ion RFQ's to energies as high as 10 MeV/nucleon. This technology would relax a severe power-based constraint on RFQ design, allowing the use of "larger-than-normal" modulations in the electrode geometry, resulting in increased electrode spacing, allowing higher voltage excitations, which, in turn, would result in improved acceleration rates at higher velocities. This technology would also offer a sizeable reduction in the required rf power for many designs and would facilitate the possibility of CW operation. Design considerations for superconducting proton and heavy-ion RFQ systems will be discussed. Several proton and heavy-ion RFQ designs will be presented together with an analysis of their performance and suggestions for practical fabrication in a superconducting format.

Introduction

Design considerations for conventional RFQ's have limited the proton versions to output energies in the vicinity of 2 MeV. By this point, the RFQ has transformed the continuous beam from the low-voltage ion source into an ideal beam for further acceleration by the magnetically-focused drift tube linac (DTL) structure. Hence, proton RFQ's have typically been a few meters in length and constrained by the remaining system to being pulsed structures. This situation provides little incentive for the development of superconducting RFQ's.

Superconducting technology may open the door on the RFQ parameter space to yield interesting proton RFQ's to energies as high as 100 MeV and heavy-ion RFQ's to energies as high as 10 MeV/nucleon. Furthermore, the RFQ configuration, shown in Fig. 1, may be easier to translate into a superconducting format than would be the conventional DTL structure. If this proves to be the case, some interesting facilities could be designed entirely on the basis of superconducting RFQ's, without dependence on parallel development of superconducting DTL's.

The RF power systems for conventional room-temperature linacs are always an expensive and complex part of the system. The potential impact of a superconducting system is most dramatic in this area. Compare, for example, the rf power requirement for the first 100 MeV of PIGMI with that of a superconducting RFQ-based system with a continuous beam of the same average power. In the case of PIGMI, the rf power requirement for the first 100 MeV of the facility is about 15 MW of pulsed power, with a pulse duty factor of 0.0036. In the 100-MeV, superconducting, RFQ case, the rf power requirement is just the beam power, namely, 100 μA * 100 MeV = 10 kW CW. The latter is readily available from the TV industry.

Design Constraints

The acceleration rate in RFQ structures is proportional to $r_o/\beta\lambda$, where r_o is the radial aperture at the point of quadrupolar symmetry and $\beta\lambda$ is the particle wavelength. The r_o parameter is a function of the minimum radial parameter, a, and the modulation factor, m. In conventional structures, power considerations force designers to keep the radial aperture and modulation factor as small as possible, consistent with the needs of the beam. For a given frequency, this results in a particle velocity, β, beyond which the acceleration rate is too low to be of interest.

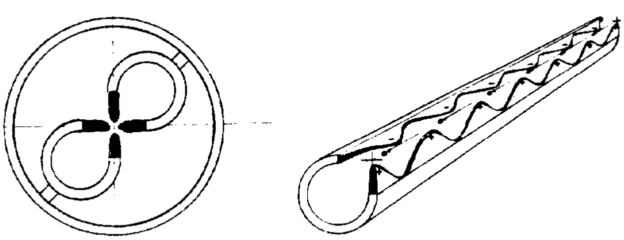

Fig. 1a. High Frequency Superconducting RFQ Structure.

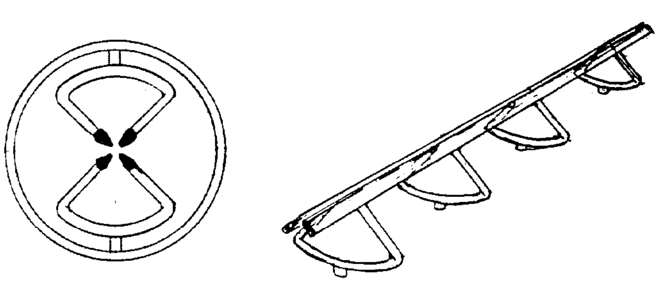

Fig. 1b, Low Frequency Superconducting RFQ Structure.

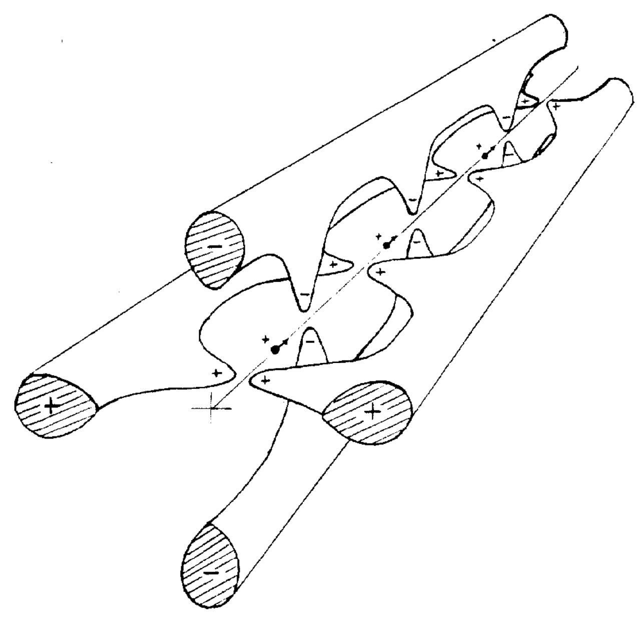

Fig. 2. Exaggerated Electrode Configuration.

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In superconducting structures, the designer is relieved of the power-based constraint, allowing him to enlarge the radial aperture and/or modulation factor and excite the structure to higher voltages to extend the range of parameters for which the structure is interesting. In such structures, however, a large fraction of the circulating energy is involved in establishing the focusing fields of the RFQ and only a small fraction of the energy is available to accelerate the beam. Hence, these structures may only be of interest in a superconducting format.

Superconducting Format

The RFQ configurations shown in Fig. 1 may be well suited for translation into a superconducting format. In both the high frequency and low frequency versions, the structure consist of pairs of identical superconducting pieces mounted opposite to each other inside a superconducting cylinder. Each of the inner pieces represents a basic unit of the structure comprising two of the four RFQ electrodes connected by an inductor. In the high frequency version, the inductor has the lowest inductance. In the low frequency version, the inductor has a higher inductance.

In both cases, the rf currents flow back and forth on the basic unit for one electrode to the other through the inductor. There is no need for currents to flow from the basic unit to or from the walls of the cavity to support the oscillation. This feature was intentionally adopted from the successful superconducting structures developed for heavy ion acceleration at the Argonne National Laboratory (the ATLAS facility).[1]

The high frequency version is similar to the original split-cylinder structure of Kapchinskii and Teplyakov. This structure was studied briefly in the early days of RFQ development at LANL. It has the advantage over the four-vane structure that the dipole mode frequencies are distinctly different from the quadrupole mode frequencies, thereby relieving some of the severe mechanical constraints that we associate with RFQ's.

The low frequency version is one of many ways that the four bars of the four-bar structure can be connected into a resonant circuit. This configuration has the advantage that the basic unit of the structure can be fabricated and tested in configurations that still provide good mechanical access to the critical electrode surfaces that the superconducting versions may require.

Longitudinally, both versions can be configured as relatively short sections mounted in one or more superconducting cylinders, as shown in Fig. 3. This has the distinct developmental advantage that the smaller units can be more easily tested and trained for high gradient operation. It has the operational advantage that troublesome units can be more easily identified, and it has the design advantage that the short sections can be designed for different excitations.

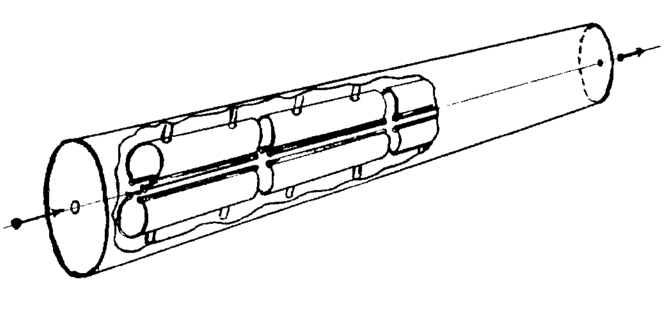

Fig. 3. Multisection Configuration.

Design Examples

Table I lists some parameters of a 200 MHz RFQ that accelerates protons from 10 to 100 MeV, where EZERO is the average axial electric field in MV/m, BB is the focusing factor, DD is the rf focusing/defocusing factor, AA is the minimum radial aperture in cm, MM is the modulation factor, and VOLT is the vane-to-vane voltage in MV. It is organized as 22 sections, each about two meters long. The total length of the 100 MeV structure is 45.15 m.

Table II lists some parameter of a 50 MHz RFQ that accelerates a mass 200 heavy ion with charge +20 from 7 to 95 MeV in a length of 2.44 m.

Table III list some parameters of a 100 MHz RFQ that accelerates any ion with a charge-to-mass ratio of 0.4 from 0.1 MeV/nucleon to 8.2 MeV/nucleon in a length of 10.47 meters.

Table I 100 MeV Proton RFQ

RFQPARM GENLIN TABLE (14) WI= 10.00 FREQ= 200.00 QOA= 1.00

NT	NC	ENERGY	EZERO	BB	DD	TLTOT	AA	PHIS	MM	VOLT
1	17	14.321	2.892	4.954	-0.046	203.597	0.500	-30.000	4.004	0.427
2	15	18.820	2.985	4.337	-0.038	412.693	0.500	-30.000	4.604	0.488
3	13	23.069	2.945	4.037	-0.032	615.802	0.500	-30.000	4.954	0.524
4	12	27.221	2.878	3.845	-0.028	820.586	0.500	-30.000	5.204	0.550
5	11	31.235	2.842	3.672	-0.025	1022.350	0.500	-30.000	5.454	0.576
6	11	35.416	2.788	3.544	-0.023	1237.118	0.500	-30.000	5.654	0.597
7	10	39.403	2.780	3.397	-0.021	1443.339	0.500	-30.000	5.904	0.623
8	10	43.539	2.752	3.288	-0.020	1659.795	0.500	-30.000	6.104	0.643
9	9	47.395	2.740	3.185	-0.019	1863.160	0.500	-30.000	6.304	0.664
10	9	51.416	2.751	3.067	-0.018	2074.519	0.500	-30.000	6.554	0.690
11	9	55.570	2.742	2.977	-0.017	2293.768	0.500	-30.000	6.754	0.710
12	8	59.407	2.764	2.873	-0.017	2495.202	0.500	-30.000	7.004	0.736
13	8	63.362	2.766	2.795	-0.016	2702.743	0.500	-30.000	7.204	0.757
14	8	67.461	2.787	2.703	-0.016	2916.342	0.500	-30.000	7.454	0.782
15	8	71.705	2.808	2.618	-0.016	3135.966	0.500	-30.000	7.704	0.808
16	8	76.093	2.827	2.537	-0.015	3361.579	0.500	-30.000	7.954	0.834
17	7	80.083	2.872	2.447	-0.015	3563.888	0.500	-30.000	8.254	0.864
18	7	84.199	2.898	2.376	-0.015	3770.767	0.500	-30.000	8.504	0.890
19	7	88.465	2.939	2.297	-0.015	3982.212	0.500	-30.000	8.804	0.921
20	7	92.881	2.978	2.223	-0.015	4198.227	0.500	-30.000	9.104	0.951
21	7	97.470	3.032	2.143	-0.015	4418.824	0.500	-30.000	9.454	0.987
22	7	102.233	3.083	2.068	-0.015	4644.020	0.500	-30.000	9.804	1.023

Table II 95 MeV Heavy Ion RFQ

RFQPARM GENLIN TABLE (14) WI= 7.00 FREQ= 50.00 QOA= 0.10

NT	NC	ENERGY	EZERO	BB	DD	TLTOT	AA	PHIS	MM	VOLT
1	14	20.614	1.691	7.996	-0.231	50.294	0.600	-30.000	1.818	0.149
2	10	39.255	2.285	6.065	-0.160	103.754	0.600	-30.000	2.568	0.197
3	8	59.304	2.477	5.086	-0.115	158.794	0.600	-30.000	3.118	0.234
4	7	81.417	2.655	4.333	-0.096	216.386	0.600	-30.000	3.718	0.275
5	6	105.264	2.934	3.630	-0.088	273.260	0.600	-30.000	4.518	0.329

Table III 8.2 MeV/nucleon Ion RFQ

RFQPARM GENLIN TABLE (14) WI= 0.10 FREQ= 100.00 QOA= 0.40

NT	NC	ENERGY	EZERO	BB	DD	TLTOT	AA	PHIS	MM	VOLT
1	23	0.808	1.844	10.512	-0.542	104.237	0.200	-30.000	5.293	0.123
2	13	1.859	3.182	4.281	-0.181	207.680	0.200	-30.000	12.893	0.302
3	10	2.755	2.885	3.877	-0.088	312.809	0.200	-30.000	13.493	0.333
4	9	3.620	2.699	3.618	-0.064	424.033	0.200	-30.000	14.293	0.357
5	8	4.437	2.591	3.408	-0.051	535.145	0.200	-30.000	15.093	0.379
6	7	5.190	2.524	3.238	-0.044	641.377	0.200	-30.000	15.843	0.399
7	7	5.979	2.462	3.095	-0.040	755.738	0.200	-30.000	16.543	0.418
8	6	6.689	2.445	2.949	-0.036	860.077	0.200	-30.000	17.343	0.438
9	6	7.429	2.418	2.833	-0.034	970.164	0.200	-30.000	18.043	0.456
10	6	8.202	2.406	2.712	-0.032	1085.929	0.200	-30.000	18.843	0.477

Fig. 4 shows the electrode geometries for Tanks 1, 3, 5 and 7 of Table III. The ridgelines correspond to solutions of the RFQ equipotential function. The radii of curvature at the ridgelines are consistent with normal RFQ design practice. The computer program that produced the figures was written by David Sweet, undergraduate physics student, Texas A&M University.

Fig. 5 shows a low frequency RFQ model (without electrode modulations) which has a diameter of 12 inches, inductive support spacing of 18 inches, and resonates at 93 MHz. This model was built by the author and Charles Swenson, a graduate physics student at Texas A&M Univ.

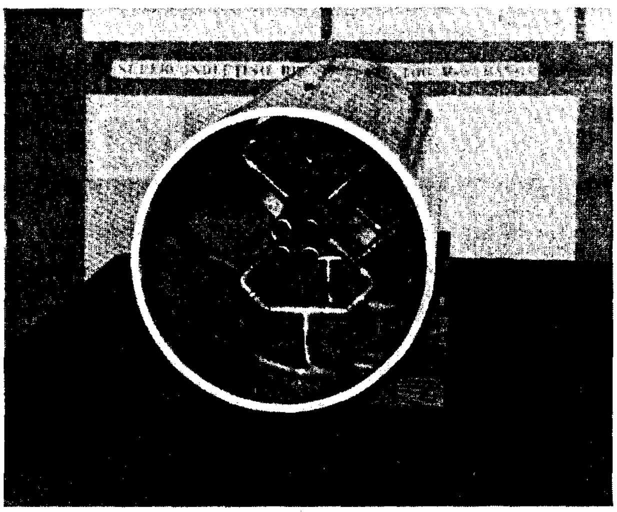

Fig. 5. A 93 MHz RFQ Model (no modulations).

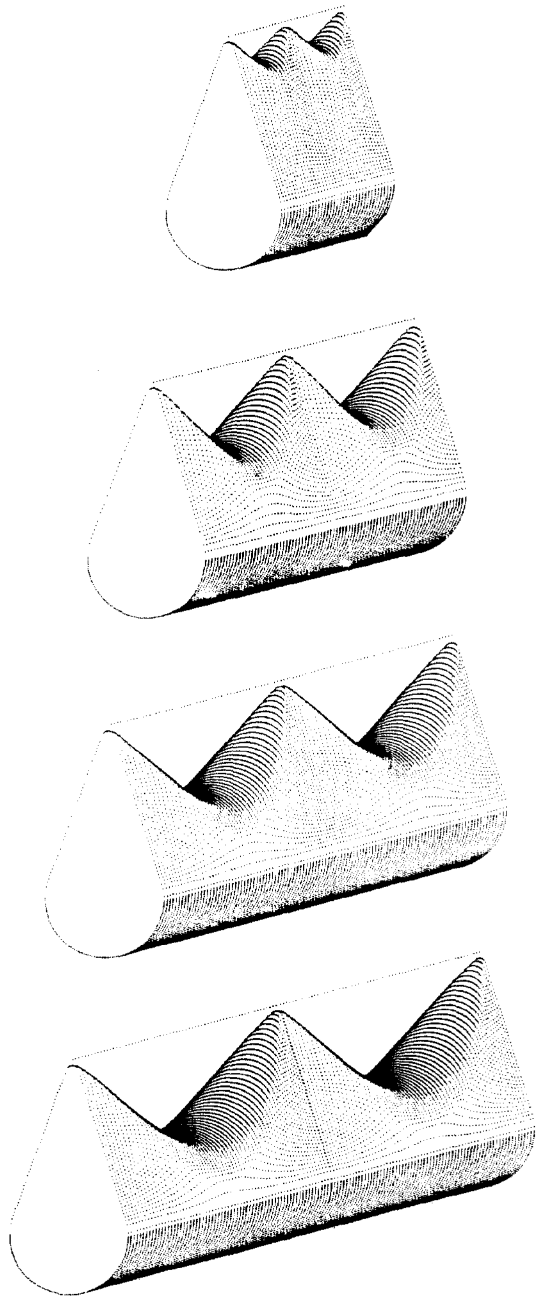

Fig. 4. Electrode Geometries for Tanks 1, 3, 5 and 7 of Table III.

Fabrication Techniques

Many of the fabrication techniques used for conventional structures are not suitable for superconstructing structures. For example, electroplating of niobium (from solution) does not work. Brazing alloys represent an intolerable contamination. The heat conductivity of niobium is poor at superconducting temperatures. Copper, on the other hand, is a good heat conductor at these temperatures.

The inner parts of the Argonne split-ring structure are made of pure niobium and are electron beam welded together. The outer cylinders of the Argonne structure are made of an explosively bonded niobium/copper sandwich. The latter is cheaper to fabricate and has better thermal properties than a pure niobium cylinder.

Chemical vapor deposition (CVD) of niobium on other base materials may prove to be an intresting mode of fabrication for superconducting structures. This would allow one to form the structure using a variety of materials and fabrication techniques and to make it all superconducting by deposition of 50 microns of pure niobium using the CVD process. In this process, a mixture of niobium pentachloride and hydrogen gas are passed through the structure at an elevated temperature (800°C), resulting in a pure niobium deposit on the surfaces and hydrochloric gas.

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