DEVELOPMENTS IN SUPERCONDUCTING SLOW-WAVE STRUCTURES

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Summary

The present situation in the development of superconducting structures can be characterized by long-term operation of full-scale superconducting systems under realistic operating conditions. Superconducting structures brought into operation with low power loss and high duty factor have been shown to maintain that performance for extended periods of time under beam line conditions. Energy gradients of 2 - 4 MeV/m, although they are less than originally hoped for, are still competitive in many applications. As a result of this experience, the important aspect of superconducting proton and heavy-ion accelerators is clearly an economic one. This has placed great emphasis on structure design at reduced cost and on simplifying the rf control and cryogenic design. The paper summarizes the status of the most advanced superconducting slow-wave resonators of the helical, split-ring, re-entrant, Alvarez and Iris type.

Introduction

The current activity in rf superconductivity is motivated by the need for particle beams of very high duty factor. Considerable experience has been gained in the operation of superconducting electron accelerators under beam line conditions at Stanford [1], at the University of Illinois[2], and at Cornell [3], whereas a design study for an experimental superconducting electron accelerator is in progress at Wuppertal [4]. A joint Karlsruhe/CERN group [5] is constructing a superconducting rf particle separator using a similar type of superconducting structure as for electron accelerators.

The number of beam experiments with low beta superconducting structures is rapidly increasing, and experience of long-term operation on full-scale superconducting systems become available. At Karlsruhe, the superconducting accelerator program is directed to intense proton beams [6], whereas at Argonne [7], Cal Tech [8], Karlsruhe [9] and Stanford [10] low beta superconducting structures are being developed for heavy-ion particle accelerators. In all of these applications low power loss and high duty factor are essential properties of the superconducting structure. The achieved energy gradients of 2 - 4 MeV/m together with rf power reduction of at least a factor of 10^4 compared to conventional room temperature accelerators are attractive for use in proton and heavy-ion accelerators. In this area superconducting structures have to compete with conventional room temperature structures [11],[12]. Therefore, most recently the work on slow-wave structures became highly focused to economically-attractive fabrication techniques for the superconducting resonators, to simplifications in the rf control system, and to cryogenic design at reduced cost.

In this area a number of different laboratories have put considerable effort in structure design and in tests for a broad range of slow-wave structures. For the superconducting proton accelerator a program has been initiated at Karlsruhe (IEKP) to demonstrate reliable performance of the superconducting helical structure. In addition, a superconducting Alvarez and slotted-iris structure are being developed [13],[14]. For heavy-ion accelerators, all programs are directed at present to the development of superconducting postaccelerators serving as an energy booster for heavy ions from a tandem. At Argonne, originally also the superconducting helical structure was studied [15]. Cal Tech proposed the split-ring resonator [8]. At present, research programs have been started at Argonne [16] and at Stony Brook [17], using different versions of the superconducting split-ring structure. Moreover, important development work on a tandem-injected postaccelerator is in progress with halfwavelength helices [9] at Karlsruhe, and with re-entrant cavities [10] at Stanford.

Scope of the accelerator

Proton linacs usually have been optimized for a fixed program of particle velocity versus position along the machine. The requirements for such fixed β accelerators for the production of negative pions or of neutrons are the following: (1) high beam intensity, (2) modest energy resolution, (3) variation of final energy in the region of 20%, and (4) reduction of the number of resonators as far as possible, because each resonator would be powered by a separate rf system. Focussing, fabrication technique and surface treatment, however, set an upper limit on the length of about 1 m for a superconducting structure.

The requirements for a heavy-ion booster as a variable β accelerator are: (1) Output beams of small energy spread to preserve the good quality of the tandem beam, (2) variation of final energy over a wide range, and (3) the ability to accelerate a wide variety of ion species (wide e/m range); therefore the number of cavities is high. This led to the concept of variable phasing techniques. An array of independently phased short resonators is used; each resonator is operated with an rf phase chosen according to the velocity of the ion to be accelerated. This provides also a direct method to vary the energy of the output beam, the possibility to control the ion beam dynamics through programming the synchronous phase, and the use of modular construction that would reduce cost and increase overall reliability.

Superconducting structures

There are many important design factors which influence the performance of a superconducting structure. They have been discussed in the literature cited in table I. Additional information will be given in the following papers at this conference. Rather than summarizing all the work reported there, I would like to restrict the discussion in this paper to the following aspects of structure design: peak surface fields, surface preparation, frequency stability and cooling.

Peak surface fields

The peak electric (E_p) and magnetic (B_p) rf fields attainable in superconducting structures are limited by various effects[18]. For the slow-wave structures, operated at low frequencies (several hundred MHz), the experience of the last few years has shown that thermal or magnetic breakdown no longer play any significant role for the field limitations. However, all structures seem to be limited by electron problems. Electron multipacting, field emission and a mixture between both effects cause electrical breakdown[19-21]. The limitation does not always occur at a sharp field level but is observed by strongly increasing power loss in the structure walls with increasing field level. Thereby, multipacting electrons deliver energy to the structure walls and a relatively small fraction of the available power is required to drive the surface normal. Even when the power adsorbed is less than required to drive the surface normal, as a result of the electron bombardment the surface quality and the critical magnetic field may be decreased. In order to keep electron problems low, an important goal in structure design should be to minimize the ratio E_p/E_o.

Electron problems are present in any slow-wave structure, if the peak electric field exceeds 10 MV/m. It is a question of design philosophy, and of course an economic question, if one wants to accept higher losses and operate a superconducting structure at field levels, where electrons from the surface are emitted. According to the present status of technology peak electric fields of more than 20 MV/m have been obtained for a shorter or longer time with nearly all discussed slow-wave structures. The highest value of 37 MV/m was observed in a $\lambda/2$-helix unit. However, at these field levels the losses are enhanced and cooling becomes an important question. A promising approach is 4.2 K-cooling, because refrigeration costs are greatly reduced and higher losses due to electron effects may be tolerated. More serious is the fact that at these high field levels the rate of electrons seems not to be constant over longer periods of time[22]. Therefore, the operating conditions for slow-wave structures at high field levels may vary due to the electron effects, and precautions in the design have to be taken.

Very often helium-processing is claimed to be a method to overcome electron emission and then reach higher surface fields. It is not clear for the author if this will hold for long-term operation. We have made contradicting experience with helices at Karlsruhe[22].

In general, the situation with respect to peak electric surface fields did not improve very much during the past few years. The best surface preparation technique did not improve the peak values. Most recently, Nb_3Sn seems to be a very promising superconductor in that respect[23].

TABLE I

CURRENT STUDIES OF SLOW WAVE-STRUCTURES

Structure	Resonant Frequency (MHz)	Particle Velocity $\beta = v/c$	Laboratory
Helix	90	0.04 - 0.10	Karlsruhe (IEKP) [6]
	108	0.06	Karlsruhe (IEKP) [9]
Split-ring	240	0.07	Cal Tech/Stony Brook [17]
	97	0.115	Argonne [7,16]
Re-entrant	430	0.10	Stanford (HEPL) [10]
Alvarez	720	0.10	Karlsruhe (IEKP) [13]
(Slotted)-Iris	720	0.20 - 0.90	Karlsruhe (IEKP) [13,14]

Surface preparation

Electropolishing, chemical polishing, oxypolishing and vacuum firing are well-established methods for the treatment of niobium to achieve clean and smooth surfaces. A new aspect on vacuum firing seems that there is no need to heat slow-wave structures to temperatures above 1200° C, and that a vacuum of about 10^{-6} Torr seems to be adequate. An exception is the re-entrant cavity at HEPL.

A new method for the surface treatment of lead has been reported from Cal-Tech[8]. A chemical polishing technique for use on electroplated lead surfaces has been developed which greatly reduces the electric field emission for electrons from the surface. The use of lead as a superconductor seems to be appropriate to the split-ring structure, only, because due to the geometry of these resonators the peak magnetic field is reduced up to factor of 2 compared to the helix.

Frequency stability

A significant problem for all structures at a frequency of 100 MHz are easily excited mechanical vibrations, and these cause the resonance frequency to fluctuate to a greater degree than can be tolerated. Therefore, it is desirable to minimize the problem by: (1) maximizing the rigidity of the accelerating structure, (2) minimizing the vibration-driving forces, and (3) using electrical-control techniques. Due to radiation pressure the resonant frequency of any structure will shift to lower values as the stored energy level increases (static frequency shift). Important progress in electronic stabilization of very low beta structures has been reported in the past few years[24,25]; therefore this static frequency shift and ponderomotive oscillations are no problem if high loop gain of the rf control unit is provided. Moreover, the static frequency shift can be used as a method of tuning individual resonators by changing the field.

The figure of merit for slow-wave structures is the variation of reactive power ΔP_b which is given by the product of stored energy U and the peak to peak excursion of the angular frequency $\Delta\omega$ induced by ambient vibration This is equal to the amount of rf power necessary to compensate for a frequency shift at the energy content U. Table II compares the properties of some slow-wave structures for a voltage gain of 1 MV.

From table II clearly the advantages of the split-ring structure with respect to frequency stability can be seen. The amount of reactive power to compensate the effect of the vibrations ΔP_b is in the order of 100 VA. Negative rf feedback is sufficient for the rf control system, and transistor power amplifiers can be used. If the amount of reactive power is in the order of several kVA, an additional fast tuner like a voltage-controlled reactance (VCX) has to be used for the helical structure. This device controls the rf phase by modulating the rf frequency by the necessary amount, with the modulation cycle being controlled by the phase error signal. A unit with an amount of ΔP_b = 4 kVA switching power in the VCX to compensate for the effect of the vibrations has been developed and successfully tested in connection with the superconducting proton accelerator at Karlsruhe. In addition, the

TABLE II

COMPARISON OF THE PROPERTIES OF DIFFERENT SLOW-WAVE STRUCTURES FOR 1 MV VOLTAGE GAIN

	Multiple-Helix (Ref. 6)	λ/2-Helix (Ref. 9)	Split-ring (Ref. 16)	Split-ring (Ref. 17)	Re-entrant (Ref. 10)	Alvarez (Ref. 13)
f_o (MHz)	90	108	97	238	430	720
Δf_{Stat} (kHz)	150	30	2.1	25	8.5	-
E_o (MV/m)	2.3	2.3	2.8	2.75	12.0	2.0
N	0.9	3.7	1.0	3.8	4.2	2.9
U (J)	0.32	0.61	1.32	0.14	1.86	0.52
$\frac{\Delta\omega}{2\pi}$ (Hz)	1000	500	120	300		10
ΔP_b (VA)	2000	2000	1000	300		30

f_o = resonant frequency, E_o = operating gradient, N = number of resonators to obtain an energy gain of 1 MV per unit charge, U = stored energy per 1 MV voltage gain, Δf_{Stat} = static frequency shift, $\Delta\omega/2\pi$ = ambient vibrations, ΔP_b = amount of rf power to compensate for the frequency shift $\Delta\omega/2\pi$.

coupling between amplitude and phase control loop could be used to increase the frequency stability of the multiple-helix. By this means the ambient vibration level could be reduced electronically by a factor 4 to about 500 Hz [26].

As can be seen from table II, the superconducting Alvarez structure is adequately stabilized at the operating field level. The re-entrant cavity should become stabilized by the addition of support struts. For the Alvarez the frequency shift due to radiation pressure was not measurable, and the vibration induced frequency excursions are below 10 Hz. But these drift-tube structures with relatively high fields on the container seem to be sensitive to the pressure of the helium bath. Therefore, double-walled constructions have been designed which are very rigid but expensive. New approaches to fabrication techniques are being developed to reduce production cost [27].

Cooling

Important effort has been put to simplify the problem of cooling and cryogenic design. There is a tendency to use 4.2 K-cooling instead of 1.8 K-cooling, because operation at 4.2 K would greatly reduce refrigeration cost (>50%). Experience with the superconducting helix and split-ring structures in the frequency region of several hundred MHz, fabricated from lead and niobium, clearly have shown that sufficiently low values of surface resistance and high fields can be achieved at a temperature of 4.2 K [28]. In connection with the tandem-injected postaccelerator program at Karlsruhe forced-flow 4.2 K-cooling has been tested for the first time with superconducting helical resonators [29]. It turned out that forced-flow cooling of helices is relatively simple: a flow of 2 l/h of liquid helium at 4.3 K is sufficient to cool about 1 W of rf power. With a gas content in this mixed phase flow below 80% the temperature increase across the heated path remains below 0.2 K. No influence on the eigenfrequency of the helix could be measured. In another experiment no significant influence on surface quality and breakdown field level could be measured in the temperature range from 1.5 K to 4.2 K[28]. For the superconducting split-ring structure the 4.2 K-cooling was tested at Argonne. High field gradients could be obtained, if the helium gas in the drift tubes is removed by a plastic tube.

Summarizing, the optimum temperature of operation of slow-wave structures is almost certain above the λ point (2.2 K), and should be 4.2 K for economical reasons. Most recently, Nb_3Sn promises to be a superconducting material for use in GHz-structures also with 4.2 K-cooling.

Development programs

Helical structure

Development programs have been initiated at Karlsruhe and at Argonne concerned with investigations of the helix accelerating structure. The helix structure has the advantage of very small dimensions at low frequencies, simple fabrication techniques and good cooling conditions. It can be used in the range of $\beta = 0.04$ to $\beta = 0.11$. Half-wave length (λ/2)-helix resonators have been fabricated from niobium and were tested under a great variety of conditions [9,15,30]. Several years of testing on λ/2-helix units showed that the maximum surface electric field E_p of a resonator operating at 100 MHz may be expected to be at least 16 MV/m and the maximum surface magnetic field B_p may be at least 60 mT. The highest fields observed are E_p = 37 MV/m and B_p = 120 mT [15]. High surface fields are stable except when exposed to extremely poor vacuum conditions.

Multiple-helix resonators in a single container have been developed [31], and a superconducting proton linac was proposed at Karlsruhe [6] that consists of nine independently phased helical units operating at a frequency of 90 MHz followed by an Alvarez unit operating at 720 MHz. The schematic layout is given in fig. 1.

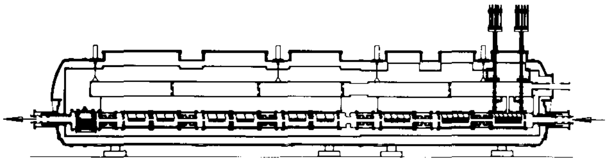

Fig. 1:
Schematic layout of the Karlsruhe superconducting proton accelerator structure. The injection energy is 0.75 MeV, and designed end energy is 6 MeV.

The present objective of the prototype is to achieve a proton beam energy of 6 MeV with a current exceeding 100 µA. In 1972, the first acceleration of a proton beam with a multiple-helix unit was achieved. A typical multiple-helix is shown in fig. 2 and fig. 3. The multiple-helix units have been designed for modest peak surface fields of E_p = 16 MV/m and B_p = 60 mT, corresponding to a maximum energy gradient of 2.3 MeV/m at a particle velocity of β=0.06.

The first two multiple-helix units were simultaneously phase locked to a common master oscillator by means of the VCX control, and a proton beam was accelerated through the pair of resonators. Phase stability within ±0.02 radian and amplitude stability within 1% were achieved continuously at the design field level. An amount of reactive power of 340 W and 415 W, respectively, at room temperature, was needed to compensate the effect of ambient vibrations.

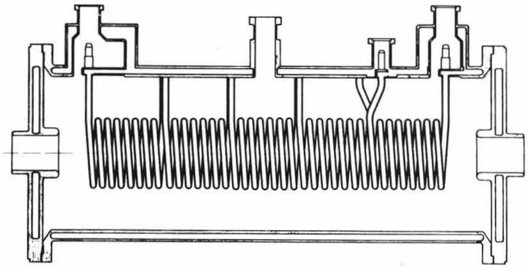

Fig. 2:
Construction of a double-walled multiple-helix for 90 MHz. The electrical length is 0.6 m, the inner diameter 20 cm.

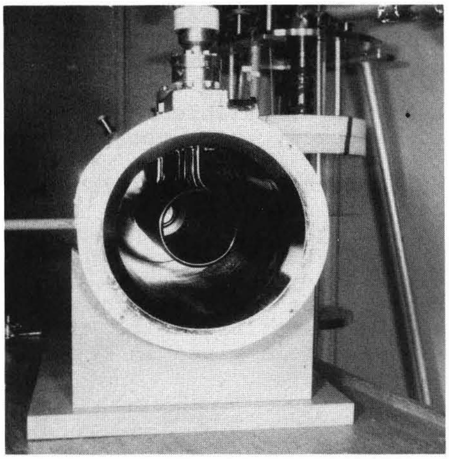

Fig. 3:
90 MHz multiple-helix unit fabricated of niobium.

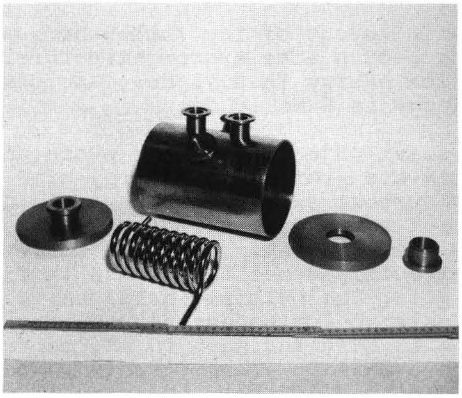

Fig. 4:
Disassembled λ/2-helix unit made from niobium. The housing is single-walled, has an inner diameter of 15 cm and a length of 23.2 cm. The resonant frequency is 108 MHz; the resonator has been designed for $\beta = 0.06$.

Based on the extended experience with the superconducting helix structure, in 1975 a tandem-injected postaccelerator with individual phased identical λ/2-helices was proposed at Karlsruhe [32], and an experimental program was started to add two helix units to the Heidelberg tandem. This program has made rapid progress, more detail will be given by Vetter at this conference [33]. A λ/2-helix is pictured in fig. 4.

Split-ring resonator

This promising new kind of structure was introduced by Shepard, Mercereau and Dick at Cal Tech [8]. Fig. 5 shows the prototype superconducting split-ring element.

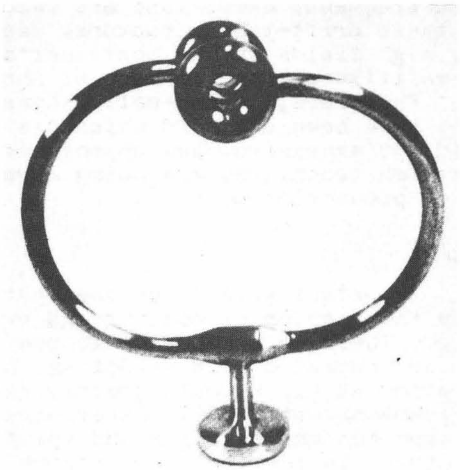

Fig. 5:
240 MHz superconducting split-ring element developed at Cal Tech. The ring is fabricated from chemically polished Pb electroplated onto copper. The diameter of the ring is 12.6 cm, the diameter of the ring tubing is 0.95 cm, and the diameter of the housing is 25 cm.

The relevant rf eigenmode of the structure is the π-mode. The ring is enclosed in a cylindrical housing, and the ring element is demountably joined through an indium vacuum seal. The split-ring resonator has the advantage of a relatively low energy content at a given accelerating field and better frequency stability compared to the helix (see table II). In addition, the peak magnetic field at a given accelerating field is lower; therefore, the use of lead plated resonators is possible. However, the split-ring resonator has considerable larger dimensions at low frequencies compared to the helix, and fabrication techniques are more complicated. Preliminary design studies indicate that the split-ring resonator will be possible to use for any particle velocity in a range of at least $\beta = 0.04$ to $\beta = 0.12$ [17].

At present, two development programs for a heavy-ion booster using the split-ring structure are in progress. A joint Cal Tech/Stony Brook group is proposing the acceleration of heavy ions of $\beta = 0.04$ to

0.15 from a 9 MV tandem [17]. Tests with heavy ion beams of ^{16}O and ^{32}S have been performed on a lead plated prototype split-ring resonator. It was designed at Cal Tech for a frequency of 240 MHz and a particle velocity of $\beta = 0.07$. It was fabricated from OFHC-copper, plated with lead and then chemically polished. Improved chemical polishing techniques have been developed for superconducting lead which yield field levels above 25 MV/m. The prototype has been operated at accelerating gradients above 3 MV/m at Cal Tech. In the beam test at Stony Brook accelerating gradients of 2.75 MV/m have been obtained with this same resonator. Therefore, this operating gradient has been used in table II for the figure of merit of the split-ring resonator.

At Argonne, a machine with a voltage gain of about 13.5 MV has been proposed for an energy booster of the tandem. It will probably consist of 6 units with β in the range 0.06 - 0.07 and 6 units with β around 0.11 . The superconducting split-ring resonator is made of niobium. The resonance frequency is 97 MHz and its active length is 35.5 cm. Thus its effective phase velocity is $\beta = 0.115$. A photograph of the interior structure of the split-ring is shown in fig. 6.

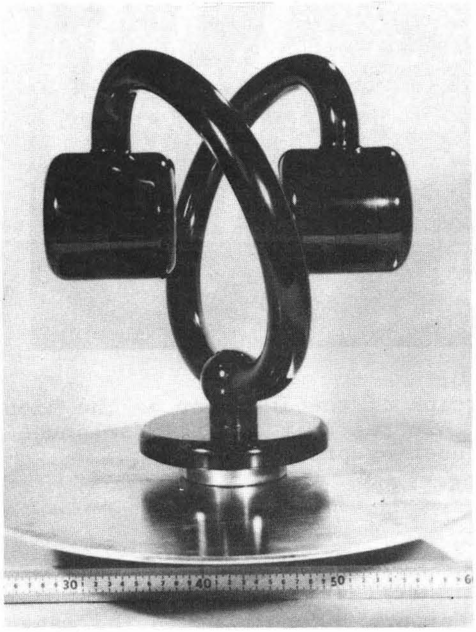

Fig. 6:
Argonne's 97 MHz superconducting split-ring structure made from niobium; length = 35.6cm, housing diameter = 40.6 cm, geometrical $\beta = 0.115$.

Notice from the photograph that the geometry of the ring has been modified from the original Cal Tech design so as to place the drift tube on the axis of the structure. The housing diameter is 40.6 cm. Fabrication of the drift tubes and ring was straightforward. However, fabrication of the double-walled housing of the resonator proved to be more difficult and costly than expected, and consequently Argonne has invested considerable effort in the development of a new approach. More detail is given by the Argonne group at this conference [16].

Re-entrant cavity

Superconducting niobium cavities of reentrant shape have been built and tested at Stanford [10]. The cavities have a 35 cm diameter, 10 cm length, and 2 cm accelerating gap. They resonate at 430 MHz. This corresponds to particle velocities of $\beta = 0.10$. Fig. 7 shows a schematic drawing of the re-entrant-cavity.

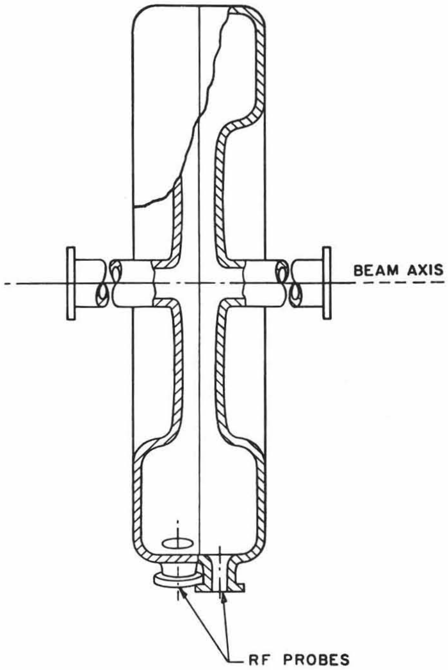

Fig. 7:
Superconducting niobium re-entrant cavity developed at Stanford. The cavity is 35 cm in diameter and resonates at 430 MHz. The gap is 2 cm wide.

A large number of tests show that the performance of the cavities is reproducible: Peak surface electric fields in excess of 12 MV/m were consistently achieved at Q-values in the range greater than 2×10^9. This operating gradient has been used in table II for the figure of merit of the re-entrant cavity. The highest field obtained was 17 MV/m, the magnetic field at breakdown was only 24 mT.

Alvarez structure

Normal conducting Alvarez structures operating between 100 and 200 MHz are in wide use to accelerate protons to the 100 MeV range. A superconducting Alvarez structure at 700 MHz is being developed at Karlsruhe for low energy protons around 10 MeV [13]. A lower frequency is not feasible because the structure diameter will become too large. The resonance frequency of a 2-cell test resonator is 720 MHz, the structure diameter is 29 cm. The test resonator has been designed for a particle energy of 5 MeV (β = 0.10), the beam hole diameter is 2 cm. The construction is shown in fig. 8.

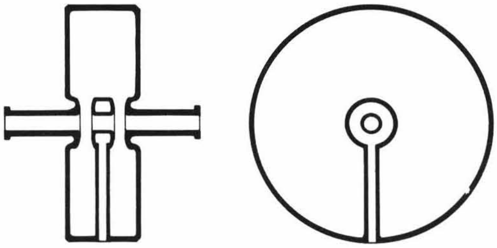

Fig. 8:
Construction of the superconducting niobium Alvarez test resonator with a diameter of 29 cm, a gapwidth of 1.5 cm, and a length of 8.6 cm. The resonator is operated in the 0-mode at 720 MHz.

The optimization of geometric parameters with respect to minimal peak surface fields was done by means of LALA-calculations. For the surface treatment after electron beam welding a special chemical polishing technique had to be developed, because electropolishing was no longer possible.

Our test results may be summarized as follows: (1) The surface treatment was good enough to achieve low field Q-values above 10^{10} at 1.8 K. (2) The resonator was operated at a surface electric field of E_p = 21 MV/m and at a surface magnetic field of B_p = 32 mT. (3) The field limitation was given by electron effects. We consider at present an energy gradient of 1.5 MeV/m at a Q-value of 2 × 10^9 to be realistic. The above mentioned peak surface fields would correspond, however, to an energy gradient of 3 MeV/m, which should be a reasonable goal for future performance.

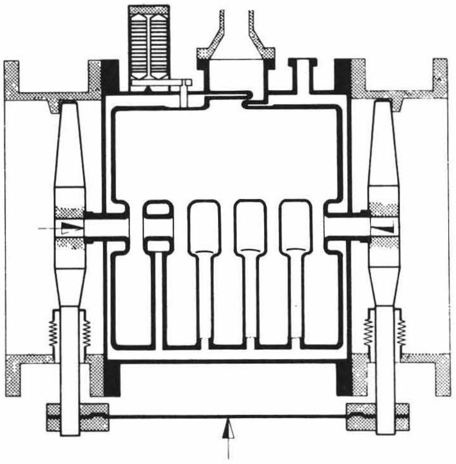

Abb. 9:
Construction of the double-walled niobium 5-cell Alvarez structure, designed for a frequency of 720 MHz and β = 0.10. The inner diameter is 29 cm, the length is 23.2 cm.

In connection with the proton accelerator program at Karlsruhe a 5-cell Alvarez unit was fabricated. The design criteria were based on the results of the test resonator. Fig. 9 gives the construction of the 5-cell Alvarez unit; fig. 10 pictures the interior.

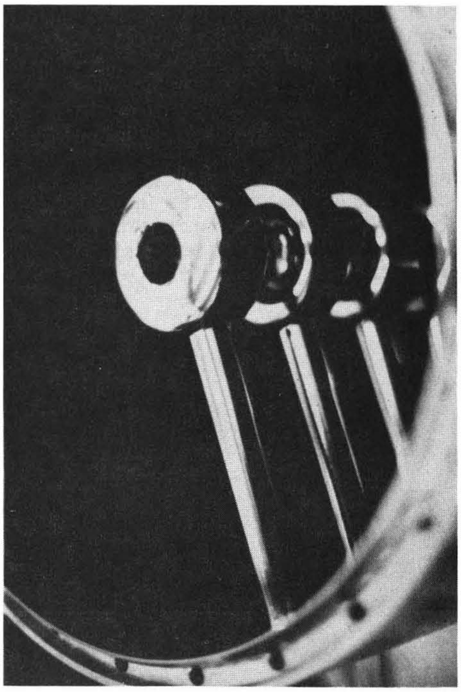

Fig. 10:
Photograph of the interior of the niobium 5-cell Alvarez unit for the Karlsruhe superconducting proton linac.

Slotted-Iris Structure

For proton energies in the range of 20 - 600 MeV (β = 0.20 to 0.90) accelerating structures of the iris type have been investigated at Karlsruhe [14]. A slotted-iris test resonator made from niobium has been developed. The resonance frequency is 720 MHz, the structure diameter is 31 cm, the design particle energy is 20 MeV. Preliminary results can be summarized as follows: (1) High field Q-values of 2.5×10^8 at 1.8 K were obtained. (2) Peak surface fields of E_p = 11 MV/m and B_p = 25 mT were achieved. (3) Field limitation was also given by electron-induced effects.

Conclusions

From the previous discussions it should have become evident that superconducting slow-wave structures are available as heavy ion boosters for tandems. Helical, split-ring, and re-entrant resonators have been fabricated from niobium. A split-ring structure has been fabricated from electroplated lead onto copper. Considerable experience and excellent performance characteristics have been obtained in the operation at helium temperatures. The best rf resonator for heavy-ion acceleration appears to be the split-ring structure on the basis of rf control requirements. However, the larger radial dimensions and the more complicated geometry of the split-ring resonator may influence the overall cost per unit. Therefore, a careful cost comparison of helical, split-ring and re-entrant type of accelerating systems may be necessary in the future.

In order to simplify greatly the mechanical aspects of the linac design and to reduce cost, new resonator fabrication techniques are being developed. Several approaches are being pursued, among them are single-walled housing, reduced number of welds and good electrochemical treatment.

The key idea on simplifying cryogenic cost is cooling by 4.2 K helium. Important results have been obtained in that respect for superconducting slow-wave structures.

The most promising rf structure for the acceleration of protons in the energy range of 5 - 150 MeV appears to be the Alvarez structure. A niobium Alvarez-resonator has been successfully tested at high field levels with low power loss. The mechanical construction provided excellent frequency stability. A 5-cell Alvarez unit has been fabricated and will be used shortly for proton beam acceleration.

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DISCUSSION

W. Jule, LASL: In the Alvarez superconducting cavity where does the peak field occur which causes electron emission breakdown?

Kuntze: At the corner of the drift tube.

Jule: Would it help if you had slanted face drift tubes instead of parallel face drift tubes?

Kuntze: No, we have optimized the shape of the drift tube according to LALA calculations. We do not have access to SUPERFISH, yet.

L.M. Bollinger, ANL: I'd like to comment on your definition of a figure of merit for the phase controllability of a resonant structure. The product $U\Delta\omega$ does not include the influence of the resonant frequency. As a result a high frequency resonator appears more favourable than is warranted by the inherent properties of the structure.

Kuntze: Yes, you are right but I thought it was too much to reduce all this to one single frequency so I reduced it to 1 megavolt voltage gain. The factor goes quadratically with the frequency and so if you compare the split ring from CalTech with the split ring from Argonne there is a factor of more than 2 in the frequency which changes the figure by a factor of 4.

E.A. Knapp, LASL: Does the statement that 4.2 K cooling is adequate mean that there is no advantage for using super fluid helium in the system?

Kuntze: Yes, you know with 4.2 K cooling systems you can reduce the refrigerator costs by more than 50% and if you use forced flow, as we have done, there is no advantage in using super fluid helium. The only advantage we had at higher frequencies is that the rf surface resistance would reduce by a large factor going from 4 K to below 2 K. That's not the case in this frequency region of 100 MHz because we are already at the residual losses.