DEVELOPMENT OF THE SUPERCONDUCTING HELIX FOR HEAVY-ION ACCELERATION*

J. Aron, R. Benaroya, L. M. Bollinger, B.E. Clifft, O.Despe, A.H.Jaffey,
K. W. Johnson, T. K. Khoe, J. J. Livingood, P. J. Markovich, J.M.Nixon,
G. W. Parker and W. A. Wesolowski

Argonne National Laboratory, Argonne, Illinois 60439 U.S.A.

SUMMARY

Recent progress in the development of the superconducting helix for heavy-ion acceleration is reported. Accelerating fields in $\lambda/2$ resonators have been pushed up to 4.6 MV/m. Phase control by means of a voltage-controlled reactance has been refined to the extent required for helix structures appropriate for projectiles with $\beta \geq 0.07$. Protons have been accelerated in a prototype accelerator consisting of two independently-phased resonators; phase control was maintained with ease, and no unforeseen problems were encountered. A prototype accelerator consisting of three independently-phased resonators, one of which is a $5\lambda/2$ unit, is nearing completion. This system will accelerate O^{5+} ions from an FN tandem.

I. INTRODUCTION

An attractive concept for heavy-ion acceleration is a tandem electrostatic accelerator injecting into a superconducting linac. The tandem provides the high initial velocity and charge state needed to minimize the design problems and the length of the linac, and superconductivity in the linac minimizes the RF problem and assures CW operation. Also, the characteristics of the tandem allow the linac to have an output beam of the highest quality.

A broad investigation of the technology required for the tandem-superconducting linac concept is being carried out at Argonne. This development program includes 1) investigations of the most important individual questions concerning the superconducting accelerating structures, 2) the construction and testing of several prototype accelerator systems, and 3) a search for economical solutions to engineering problems. This paper is a brief summary of highlights of the program for the past year. Earlier results are given in Ref. 1-3.

To date, all of our experimental work has been concerned with the helix accelerating structure, for which the range of optimum performance is well matched to the velocity range of interest for a tandem-linac heavy-ion accelerator — the range $\beta = 0.04\text{-}0.2$. These investigations have been carried out with $\lambda/2$ units made of niobium metal. RF resonance frequencies have ranged from 60 to 100 MHz. Illustrations of such units and some of the fabrication procedures have been reported previously.[1,2] The next step, the fabrication of a $5\lambda/2$ resonator, is nearing completion.

The design parameters of the helix resonators tested to date are summarized in Table 1. Note that most of these units have undergone many cycles of surface preparation (typically polishing and anodization) followed by tests of resonator performance. Thus, the total number of sets of active surfaces that have been studied is quite large - over 50.

II. ACCELERATING FIELD

In October 1972, we reported that accelerating fields of about 2.7 MV/m had been obtained with a superconducting-helix structure and that the performance characteristics could be stabilized by anodizing the niobium surfaces. Since that time, the maximum field has been substantially increased, and most other aspects of resonator technology have been improved and are better understood. The present status is summarized below.

Maximum Field

Recently the axial accelerating field E_{ax} of a helix resonator was pushed up to 4.6 MV/m, the highest field reported yet for a structure operating near 100 MHz. Also, as shown in Fig. 1, the Q of the system (Unit C) is extremely high — about 10^{10} at low fields, which corresponds to a surface resistance of about 5×10^{-10} ohm. It is believed that the sharp drop in Q above $E_{ax} = 3$ MV/m results from electron field emission from the central turns of the helix, since the drop in Q is accompanied by high-energy X rays. Note (in the caption of Fig. 1) that the superconducting surfaces used in the measurements were bare (not anodized).

A resonator (Unit A) with anodized surfaces has also given $E_{ax}(\max) = 4.5$ MV/m, although with much lower Q than for Unit C. In view of the high Q obtained previously[1] with Unit A, it seems probable that the low-Q behavior is not intrinsic but rather results from some surface flaw that has not yet been identified in continuing investigations.

The cause of the extraordinarily high fields exhibited by Units A and C has not been established. However, it might be significant that these two units are (in their present form) the only two units that have undergone two heat treatments with electropolishing after each treatment. Investigations of this question are continuing.

Helium Discharge Conditioning

Following the lead of workers at Stanford and at Siemens, we now routinely use helium discharges in operating superconducting resonators to "condition" the active surfaces. For anodized surfaces, this process almost always increases the maximum achievable field (typically by 30%) and the process also makes it easier to penetrate a low-field multipacting barrier.

A typical example of the improvement achieved by means of helium conditioning is given in Fig. 2. Here one sees that the process gradually and reproducibly extends the Q vs E_{ax} curve toward higher fields. Associated with this extention is a dramatic decrease in the intensity of X rays generated at a given field.

Table 1. Design parameters of $\lambda/2$ helix resonators that have been studied. The last column gives the number of new sets of surfaces studied in each unit.

Unit	Helix Radius (cm)	Helix Length (cm)	Helix Pitch (cm)	No. of Turns	Cavity Radius (cm)	Cavity Length (cm)	RF Frequency (MHz)	Max E_{ax} (MV/m)	No. of Test Cycles
A	3.25	11.0	1.00	11	9.75	20	96.9	2.7	2
B	3.25	11.0	1.00	11	9.75	20	99.4	1.7	5
B′	3.25	11.0	1.00	11	9.75	20	96.7	3.5	13
A′	3.25	11.0	1.00	11	9.75	20	95.8	4.5	4
C	3.25	11.0	1.00	11	6.5	20	91.9	4.6	10
E_1	4.40	12.2	1.016	12	8.8	16	62.9	1.3	1
E_2	4.40	12.2	1.016	12	8.8	16	63.1	1.1	1
G_1	3.30	12.2	1.016	12	8.8	16	91.6	2.5	9
G_2	3.30	12.2	1.016	12	8.8	16	91.6	3.2	7

For bare surfaces (for which our experience is not very extensive yet), the beneficial effects of helium-discharge conditioning are less consistent. When a unit with a bare surface is first put into service, the response to helium conditioning is similar to that for an anodized surface – that is,clearly beneficial. However, when the unit has been used and then exposed to air, helium conditioning usually does not increase the maximum field.

Stability of Bare and Anodized Surfaces

We have repeatedly demonstrated that resonators with anodized surfaces do not deteriorate when exposed to the atmosphere or when operated for long times at high fields. Indeed, high-field operation usually causes the performance to improve, probably from effects that are similar to those involved in the helium conditioning. This improvement may result from the movement of absorbed gas from sensitive surfaces to less sensitive parts of the resonator.

Recent studies of resonators with bare surfaces indicate that the bare surfaces are not as unstable as we had previously thought. For example, in Unit C, which gave a maximum field of 4.6 MV/m with a newly prepared bare surface, the maximum field dropped to 3.0 MV/m after the unit had been exposed to the atmosphere for several hours. The maximum field remained stable at the level of about 3.0 MV/m after further exposure to air.

Reproducibility of Fabrication Techniques

There are two aspects to the question of resonator-fabrication reproducibility. One involves the performance of a set of resonators of the same design, and the other involves the performance of a set of resonators with similar but differing designs.

Most of our experience to date is for resonators with the same or almost the same design. Experience of this kind includes repeated tests on single resonators whose surfaces are reprocessed (polished and anodized) before each test. Originally, the reproducibility of performance characteristics was poor. However, this problem has been largely eliminated by using greater care in surface preparation and assembly. Key elements in the present procedure are thought to be (1) rigid control of parameters in the electropolishing process, (2) the use of oxypolishing (anodization followed by stripping of the oxide) to remove surface impurities that may be left after electropolishing, and (3) final assembly of the resonator components in a dust-free "clean room".

The reproducibility of units with differing geometries is not yet satisfactory. In particular, the G-type units of Table 1, which differ from the others principally in having a smaller distance between the helix and the end plates, have not consistently performed well. This is not understood with certainty, but some of the curves of Q vs E_{ax} have characteristics that suggest that multipacting may be responsible. In any case, poor behavior of the two G-type units strongly suggest that it is inadvisable to have the end plates close to the helix.

III. VIBRATION CONTROL

Even when a helix resonator is carefully isolated from its surroundings, mechanical vibrations cause the RF resonance frequency to fluctuate more than can be tolerated if the RF phase must be controlled. To date, our approach to this problem has been to use a voltage-controlled reactance (VCX) to modulate the resonance frequency in such a way as to maintain a constant average frequency. The VCX consists of a $3\lambda/8$ transmission line terminated by a PIN-diode switch. The operation of the switch causes the impedance seen by the helix to change by $\pm jZ_0$, where Z_0 is the characteristic impedance of the line; and this impedance change causes a change Δf_0 in the resonance frequency of the helix-VCX system. A full description of our initial experience with the VCX technique of phase control is given in Ref. 3.

Nonlinear Effect

During the past year it has become clear that the principal limitation on a VCX is not set by the total RF-power loss in the system but rather by a nonlinear component in the loss, an effect that tends to enhance the mechanical vibrations whose effects one is trying to control. Although the cause of the

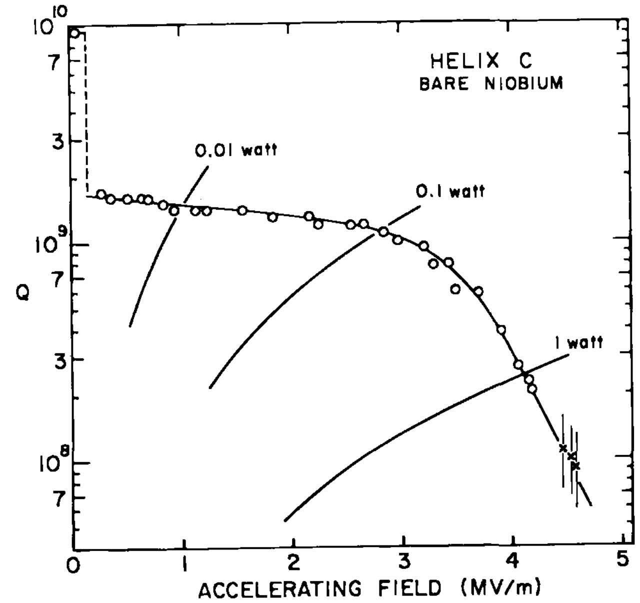

Fig. 1. Best performance of resonator C. The niobium surfaces were bare (not anodized) for these measurements.

nonlinear effect is not well understood, the magnitude of the effect can be reduced substantially by operating several diodes in parallel. This approach has probably not been pushed as far as it could be, but systematic measurements have shown that 6 diodes in parallel are better than any lesser number for our diode pulser. Presumably, the optimum number of diodes depends on the switching current available from the pulser.

Cooled Diodes

Another significant development has been the demonstration that the switching time of a PIN diode can be reduced by an order of magnitude by cooling it with liquid nitrogen. For example, the Unitrode type-4010 diode, which normally has a carrier lifetime of about 7 µsec, has the lifetime reduced to about 1.5 µsec when it is operated at liquid-nitrogen temperature. This enables one to use diodes that have higher power ratings than the type-7206 diode, which was originally thought to be the only useable type.

Test Results

The λ/2 helix resonator (Unit G_2) that happened to be operational during the final tests of the VCX system was defective and could provide an accelerating field of only 1.7 MV/m. The frequency changes caused by mechanical vibrations in this system were controlled with ease. Specifically, the vibration-induced Δf_0 was only about ± 125 Hz, whereas the VCX-induced modulation was about ± 400 Hz. Thus, since the VCX control range is inversely proportional to the square of the accelerating field, it seems certain that the G_2 resonator could have been controlled at an accelerating field of 2.5 MV/m.

During the acceleration tests described in the next section, some attention was devoted to the influence on the VCX of a fluctuating beam load. It was found that phase control could be maintained up to a proton-beam current of 14 µA for a wildly fluctuating beam. This level of performance is near that required for a practical heavy-ion accelerator.

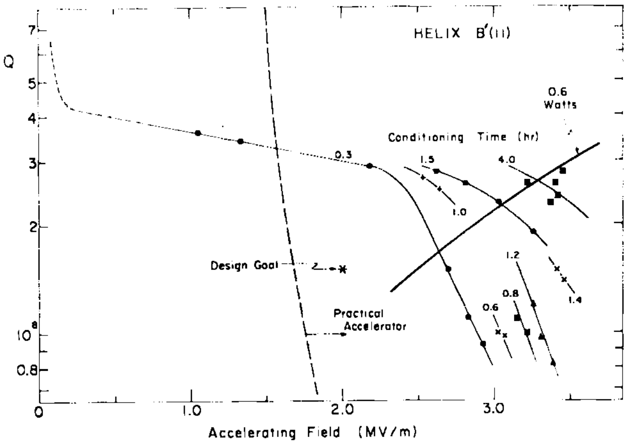

Fig. 2. Influence of helium-discharge conditioning.

Tubing Diameter

A recent conceptual advance has been the development of a quantitative understanding of the relationship between the mechanical stiffness of a helix and its vibration control. Since the vibration amplitude depends on the parameters involved in different ways for various modes of excitation, the relationships cannot be stated concisely. However, typically the amplitude depends on d^3, where d is the diameter of the helix tubing. Consequently, vibration controllability is greatly improved if the tubing diameter can be increased. This consideration has led us to increase to 3/8 inch the tubing diameter of a 5λ/2 resonator now near completion, whereas from an electrical point of view 1/4 inch is better. It is expected that two VCX units of the tested design will be able to control the phase of this large resonator up to $E_{ax} \leq 2.0$ MV/m.

Summary of Present Status

Our conclusion from the considerations and results outlined above is that the VCX technique is adequate for the control of accelerating structures of the kind required for heavy-ion beams with $\beta \geq 0.07$. The technique is borderline for lower velocities. Development of another technique has started.

IV. PROTOTYPE ACCELERATORS

The prototype-accelerator program now in progress has three phases: (1) acceleration tests with single λ/2 helix resonators, (2) acceleration tests with a system of two independently-phased λ/2 helix resonators, and (3) acceleration tests with a system of three independently-phased resonators, one of which is a 5λ/2 unit.

Individual Resonators

The work on the individual λ/2 units was described in Ref. 2. The experimental arrangement was the same as is shown in Fig.3 except

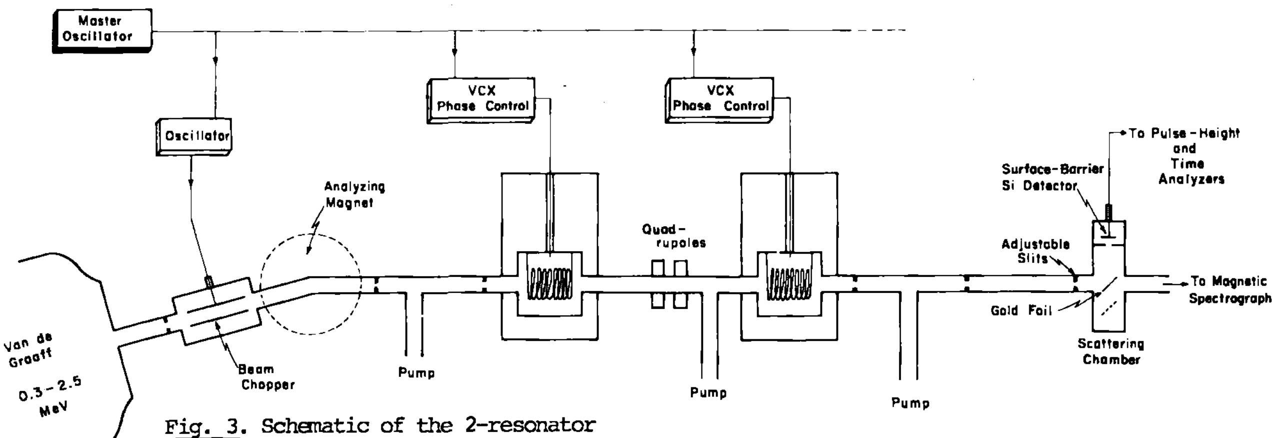

Fig. 3. Schematic of the 2-resonator prototype accelerator. The resonators are Units G_1 and G_2.

that only one resonator was used. Proton beams were accelerated in two different kinds of structures for long periods of time (a total of about 130 hours of beam time), and no unexpected problems were encountered. The measured energy gains are in good agreement with what is calculated from measurements on a copper model at room temperature.

The measured dependence of the transit-time factor on projectile energy is given in Fig. 4, where the relative energy gain $\Delta T/\Delta T_s$ is plotted as a function of the energy $(T_i + \frac{1}{2}\ \Delta T)$ of the proton at the center of the helix; here the normalizing constant ΔT_s is the energy gain for a synchronous particle, and T_i is the incident energy. As is indicated by the smooth dependence of $\Delta T/\Delta T_s$ on projectile energy, the measurements were quite accurate and reproducible.

The curves associated with each set of data points were calculated from the field distributions measured in copper models at room temperature. The good agreement indicates that the field distributions of the copper model and the superconducting structure are closely the same, as expected.

2-Resonator System

A schematic of the 2-resonator prototype is given in Fig. 3, and the system is described in Ref. 2. The main objective of the tests with this prototype was to study phase control in a working system of resonators. The phases of both accelerating units were locked to the phase of a master oscillator by means of VCX control units of the kind described in section III.

Since we do not yet have any means of coarse tuning a resonator after it is placed within its cryostat, when the two resonators have frequencies which are matched at low fields, they must always operate at the same field; otherwise, differences in radiation pressure will cause the two resonance frequencies to be different, and phase control is impossible. This limitation will not be present in a full-scale accelerator, of course, because in it each resonator will have a coarse tuner, probably an externally-controlled mechanical adjustment. However, because of the lack of coarse tuning on the prototype

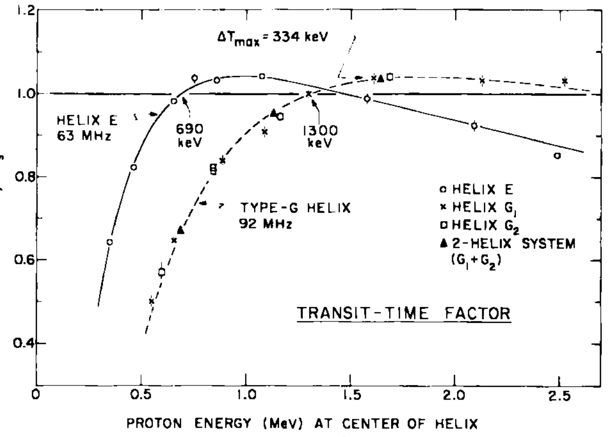

Fig. 4. Results of energy-gain measurements.

units and because of the poor performance of one of the resonators, in the tests carried out to date the accelerating field was limited to 1.0 MV/m. This limit could be greatly increased now, but it has not seemed worthwhile to repeat the measurements because of the effort being devoted to the preparation of the multiple-helix resonator described below.

An interesting detail concerning the 2-helix system was the ease with which the two units were tuned to approximately the same RF resonance frequency before they were placed in their cryostats. A simple mechanical device was used to deform the helices and in this way to match the two frequencies within about 10^3 Hz – that is, to one part in 10^5.

Objective evidence of the successful operation of the two-helix system is provided by a measurement of energy gain ΔT as a function of incident energy. Since the energy gain was small compared to the incident energy, the energy dependence of ΔT should be the same for the two-helix pair as it is for an individual unit. This was found to be the case, as is shown by the data in Fig. 4.

The 2-helix system was operated with phase control for several hours, and no unexpected problems were encountered. The energy gain of the system was shown to be equal to the sum of the energy gains of the individual resonators. Phase control of the system could be maintained up to a beam current of 10 μa.

Multiple-Helix Prototype

Construction of a multiple-helix prototype consisting of two single λ/2 resonators and one 5λ/2 resonator is nearing completion, and components are beginning to be assembled on a beam line at the FN-tandem injector. The main objective of the project is to gain engineering experience with a multiple-wavelength resonator of the type needed for a practical accelerator.

The design of the 5λ/2 resonator is optimized for the acceleration of O^{5+} ions with an incident energy of about 2.8 MeV per nucleon. The maximum energy gain of the accelerator system is expected to be about 2 MeV per charge. The beam current will be low because the pulsed beam is formed by a simple chopper.

The phases of the resonators will be controlled by VCX units of the type described earlier – one unit for each λ/2 resonator and two units for the 5λ/2 resonator. As mentioned in section III, the helix in the 5λ/2 resonator is made of 3/8 inch tubing in order to limit the amplitude of mechanical vibrations. Also, for the same reason, the supporting stubs are short and very rigid.

The cryostat for the 5λ/2 resonator is a helium-pumped system in which the temperature of the liquid-helium bath is designed to operate at about 1.8°K. The principles of operation are the same as for the cryostats of the λ/2 units (see Ref. 2) except that the insulation vacuum and the resonator vacuum are separate.

As far as is foreseeable, the principal question about the proper functioning of the 5λ/2 resonator is whether the technique of surface preparation that has worked well for the λ/2 units can be successfully applied to the larger 5λ/2 unit.

References

*Work performed under the auspices of the U.S. Atomic Energy Commission.

[1] R. Benaroya, A.H.Jaffey, K. Johnson, T. Khoe, J. J. Livingood, J. M. Nixon, G. W. Parker, W. J. Ramler, J. Aron, K. E. Gray, and W. A. Wesolowski, in Proc. 1972 Proton Linear Accelerator Conference (Los Alamos Scientific Laboratory Report LA-5115),p. 168

[2] J. Aron, R. Benaroya, L. M. Bollinger, K. E. Gray, A. H. Jaffey, F. J. Lynch, K. W. Johnson, T. K. Khoe, J. J. Livingood, J. M. Nixon, G. W. Parker, W. J. Ramler, and W. A. Wesolowski, in Proc. of the 1973 Particle Accelerator Conference (IEEE Trans. on Nucl. Sci. NS-20, No. 3) p. 76

[3] O. D. Despe, K. W. Johnson, and T. K. Khoe, in Proc. of the 1973 Particle Accelerator Conference (IEEE Trans. on Nucl. Sci. NS-20, No. 3) p. 71