PROGRESS REPORT ON SUPERCONDUCTING PROTON LINACS

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Summary

The work on superconducting proton and heavy ion accelerators will be reviewed. The helix seems to be an adequate structure for low velocity particles. For energies above 15 MeV/N other types of accelerating structures may be used. Superconducting Nb helices were developed at several places. A maximum gradient of 2.8 MV/m with a Q of $2\cdot10^9$ has been obtained recently in Karlsruhe with a $\lambda/2$ Nb helix at 90 MHz. First proton acceleration in superconducting helical structures indicates the status of the new technology.

Introduction

The possible application of a superconducting proton linac to high energy physics is considered, to the authors knowledge, at Karlsruhe only. However, many problems involved in building a superconducting proton linac with high energy gradient and unity duty factor are similar to heavy ion accelerators. There are a number of different groups which are developing superconducting heavy ion linacs. As far as informations on the different projects are available the results from other laboratories will be included. The progress report will be based, therefore, mainly on the results of the superconducting proton linac at Karlsruhe. More details and results of other groups will be given in several papers this afternoon.

I agree with P. B. Wilson (2) who announced at the Los Alamos conference last October if not the birth, then at least an important turning point in the history of this new technology. We are now in the status of operating prototype accelerators. The main problem left is to demonstrate, that a superconducting accelerator is a more economical and a better solution for many applications than a normal conducting one. The new technology has given emphasis, moreover, to the development of improved cryogenic systems. The combination of rf techniques and low temperature techniques has started a growing interest for industrial applications.

Proton and ion accelerators

Proton and ion accelerators have special requirements which include low phase velocity, longitudinal phase focusing and transverse focusing. There is a preference for operating at low frequency, therefore. Low frequency structures have in general large dimensions which are expensive to fabricate, to cool down and to shield against noise and thermal radiation. Experimental results on Nb resonators showed that the losses do not decrease with frequency proportional $f^{1.7}$ (3) as expected from BCS-theory. It seems clear by experiments that additional losses exist in low frequency structures, which are field dependent and which may depend on the size of the total surface area (4). The old argument in favour of low frequency in the case of rf superconductivity thus is not true, any longer. On the contrary, an argument against low frequency structures comes from the preparation techniques of superconducting surfaces. The problem of avoiding contamination of Nb resonators during different surface preparation stages and during assembly obviously increases with increasing surface area. Therefore, low frequency and small surface area are favorable.

Two different kinds of accelerating structure have been considered in more detail, so far. The Stanford group has looked into the construction of separately phased re-entrant cavities for a heavy ion linac (5). Karlsruhe (6), Argonne (7) and Cal Tech (8) decided to use helical loaded cavities for the following reasons:

1) quite small transverse dimensions (surface area exposed to high rf fields comparable to an X-band resonator)
2) low frequency (50-100 MHz)
3) large acceptance
4) coupled structures are possible (1m)

The merrits of both, reentrant and helix structure were compared in theoretical studies by Ben Zvi at Stanford (5) and by I. Khoe at Argonne (9). Single $\lambda/2$ helices gave good experimental results, gradients up to 2.8 MV/m at a Q of 2×10^9 have been obtained (10). Single $\lambda/2$ helices can be used for heavy ion linacs and give good flexibility (7,11). This kind of flexibility is not needed for a proton linac. Several $\lambda/2$ helices can be combined in a common outer tank, therefore, forming longer accelerator sections. The total length of each section is only given by fabrication and acceptance considerations. At Karlsruhe, we have built two 0.5 m sections, each consisting out of five $\lambda/2$ helices. The first section is designed for an injection energy of 0.75 MeV/N at 90 MHz. For the accelerator, it is the most difficult section at this low energy and the gradient was restricted to values between 1.0 and 1.3 MeV/m, therefore. The next sections will be designed to somewhat higher gradients. The helical structure was developed as a combined effort of our group and a group at the university of Frankfurt (12), which has been experimenting with helix accelerators for several years.

There are some requirements for a superconducting proton linac which differ from that of an electron accelerator. On one hand these requirements are connected with the choice of the low β structure, the results obtained are directly relevant to heavy ion accelerators. On the other hand these requirements are connected with the aim to accelerate protons with very high beam current for the abundant production of pions. Some special requirements are:

- mechanical damping of the whole accelerator system to avoid external noise, which in turn shifts the resonance frequency. This problem is severe for helical structures, but also exists for reentrant cavities.
- a suitable rf system with a fast tuning device to keep the phase deviations between individual accelerator sections below 1°. The helix structure shows strong ponderomotive effects at high rf field levels, which in turn can cause instabilities. Rf control loops have to counteract these instabilities.
- strong superconducting rf coupling devices at helium temperature to handle beam powers in the order of kW. The ratio of beam losses to wall losses at a current of 1 mA can be as high as 300.
- a chopper-buncher system providing short bunches with clean spaces in between. This is needed, because dissipation of heat at low temperature and possible radiation damage in the superconducting surfaces have to be reduced. If 10% of a 1 mA beam of 1 MeV would be lost 100 W of heat would be dissipated into the helium.

Accelerating structure

At Karlsruhe, we decided to build a prototype superconducting proton linac (13). This prototype is being constructed and tested as a pilot accelerator for a potential larger proton accelerator with a current of 1 mA at a unity duty factor and an energy in the range of 0.5 to 1 GeV. We decided to use superconducting Nb helical cavities as accelerator structure to achieve the high fields and the low phase velocity required for the protons at the low energy and of the accelerator (fig. 1).

For the accelerating structure cooling considerations resulted in metallically supported $\lambda/2$ helices (14).

The helices were made out of Nb tubes of 6.3 mm o.d.They were electron beam welded into a Nb top plate which has rf and helium supplies and serves as helium reservoir. Each section contains five $\lambda/2$ helices which form a replacable Nb unit (fig. 2). This unit is flanged into a lead plated outer Cu-resonator with a diameter of 40 cm and which has cooling channels etched into the walls (fig. 3). For the third helix sections the outer tank will be made out of Nb, too, with 12.5 cm radius. Then the lossy Pb/Nb joint is avoided for the future sections. After the fabrication of the helix sections the field profile was checked with bead measurements and the frequency was retuned mechanically to the design values. A field flatness of better than $\Delta E/E = 4\%$ was obtained. The preparation technique used for the superconducting surfaces was electropolishing and anodising (14). All Nb parts were electropolished several times during different fabrication stages and finally anodized to get a Nb_2O_5 layer thickness of about 400 Å.

At Stanford, design considerations for a heavy ion linac for the Weizmann institute in Israel have been made (5). Re-entrant cavities were chosen as the basic accelerating structure. There is a contribution to this conference on that subject.

At Argonne, the concept of a heavy ion accelerator involves a tandem electrostatic accelerator with two stripping stages followed by a superconducting helix accelerator (7). Several independently phased helical Nb resonators have been developed. More details will be given in a paper this afternoon.

At Cal Tech, a prototype accelerator is being constructed consisting of several indepently phased helical lead resonators. Accelerating fields of about 1 MV/m are expected (8).

At Oak Ridge, the feasibility and cost of a superconducting heavy ion linac has been studied (15). A configuration consisting of 20 MV tandem plus helical Nb linac was chosen. 1 m sections have been proposed.

At Los Alamos, a normal conducting helix accelerator for heavy ions with 150 independently phased sections has been proposed.

Rf system

In order to bypass the problem of compensating large frequency shifts, the generator frequency was matched to the resonant frequency of the helix sections by means of a phase control loop (VCO-operation). (see fig. 4). Detailed studies of ponderomotive effects as a function of different rf parameters have been done (16). The static frequency shift was of the order expected from single helix experiments. The helix frequency jitter due to external mechanical distortions can be as high as 100 kHz peak to peak. By a suitable mechanical damping of the whole cryostat this has been reduced to about 3 kHz, or 3×10^{-5} of the resonance frequency. Still further improvements on the damping system are necessary.

The concept for rf control is now to adjust the helix resonance frequency to a fixed master oscillator frequency by a fast electrical tuner. The tuner has to modulate a suitable amount of the reactive power stored in the resonator, which is of the order of 10^8 VA (VCX-operation, see fig. 4). We decided to use PIN diodes for the tuner (17). The tuner consists of a symmetric arrangement of 12 shorted coaxial lines with a length variable by a PIN diode switch (fig. 5). Since the superconducting helix and the coaxial line of the tuner together with the strong rf coupling form a system which exchanges reactive power, the resonance frequency of the helix is variable by switching the PIN diodes in discrete steps. The basic idea in selecting a symmetric arrangement of n PIN diodes consists in the fact, that the eigenfrequency is determined by the number of switched diodes only, regardless which diode has been switched. All diodes are equally loaded. The loss power of a diode is increasing linear with the switching frequency. With 12 PIN diodes the switching frequency for each diode is reduced and a considerable higher reactive power can be handled. The diodes are switched within 0.3 μsec between opened and switched state by driver amplifiers, which are triggered by a counter in a definite order.

The coaxial line arrangement has been completed and tested with a single helix at low temperature and at low rf field levels. There is a contribution to the proceedings of this conference which describes the fast tuner in some more detail (18). The essential results are the following: fixed frequency operation with phase control loop alone was possible (VCO/VCX-operation) within a tuning range of ± 1.5 kHz, the remaining phase error was 0.4°. The tuning range possibly can be expanded to about ± 4 kHz using longer stublines. An amplitude control loop seems to be necessary, since the fast tuner causes an amplitude modulation.

Strong rf coupling

Each accelerator section contains two strongly coupled rf-lines. The input line has to carry merely the power loss of the tuner and the beam power which, added, amount to typically 2 kW per meter section length. More stringent are the requirements for the output line connecting the tuner at roomtemperature to the s.c.section. Reactive powers of several kW must be handled. Reasonable cross sections of that line result in a Q of approximately 10^3. As a consequence power losses of some Watts have to be cooled at low temperatures in a way that minimizes any additional heat loading of the superconducting helix which is galvanically coupled directly to the center conductor of the line.

This is achieved by inserting cooling chambers as sections into the line each of them terminated by a pair of ceramic windows. Use of liquid N_2 and He as cooling fluids and favourable spacing of these cooling sections allows to optimize for minimum heat transfer into the liquid helium. First, two lines, each one containing a cooling chamber at He temperature, have been tested in conjunction with the second accelerator section and were found to operate successfully up to an axial accelerating field of 1 MV/m. Stresses involved by the rigid center conductors lead to a failure of one of the ceramic windows so that gas discharges prevented to obtain higher field levels.

Injection system

We start acceleration with a well tested inexpensive Cockroft-Walton set with an energy of 750 keV and a Duoplasmatron ion source. Up to now a continuous total beam current of 1.3 mA is available at the exit of the accelerating column. The requirements for the chopper-buncher system are strict, because particle loss on the accelerator structure has to be reduced. Such loss could heat up and damage the superconducting surfaces. The necessary frequency jump along a larger proton accelerator reduces the longitudinal acceptance even more.

These requirements could be met by a combination of energy modulation and momentum analysis by a deflecting magnet (19). The monoenergetic proton beam passes first an energy modulator (fig. 6), which is an rf cavity driven at the fundamental frequency of 90 MHz (20). The proton beam is subsequently momentum analysed by a 270° deflecting magnet (270° for geometry and symmetry reasons). There is a focus halfway in the deflecting magnet where an edge permits only the lower momentum particles to pass. These protons pass the energy modulator again(fig.6), in our special geometry under 90° to the first time. The energy modulation will be compensated to a high degree and in addition an energy distribution as function of time is imparted. The final energy modulation is ±2.1% with an rf power consumption of about 700 W. The particle bunches will be bunched in phase to about 22° by the time they enter the accelerating structure. The system is partly tested with an injected beam of 1 mA and gave so far the design values (21). A bunched beam with 400 μA is now available at the entrance of the superconducting accelerator. The bunched beam has been accelerated successfully with the first helix section(fig.7). The energy spread after acceleration has not been measured so far due to the poor resolution of our preliminary energy analysing system.

Conclusions

The Karlsruhe results on three experimental runs, each extending over several weeks, can be summarized as follows:

1. Stable operation at designed field levels was achieved and a pulsed proton beam of 4 μA has been accelerated with one helix section formed out of five λ/2 helices. The beam was limited by the rf coupling device, that was not designed for transmitting high power. Maximum gradient was 1.4 MV/m.
2. Cryostat and superfluid cooling were adequate. The cryostat has a two vacuum system, the beam vacuum is separated from the insulation vacuum. Super leaks existed below the λ-point, but did affect the whole experiments only slightly (22).
3. An rf coupling device designed for transmitting high power was developed and had been partly tested with the second helix section.
4. A fast tuner consisting of a symmetric arrangement of 12 coaxial lines shorted by 12 PIN diode switches was developed and tested at low temperature single helix experiment. The tuning range is ± 1.5 kHz, the absolut phase error 0.4°. The tuning range can be increased.
5. A chopper-buncher system for the injection system was developed and gives proton bunches which come close to the design values.

At present, all efforts are concentrated to operate the two uncoupled helix sections in sychronism. The second helix cryostat has been designed and will be ordered soon. New ways in the fabrication of additional helix sections are considered. In a single helix experiment maximum fields of 2.8 MV/m and 700 G have been obtained at a high field Q of 2×10^9. The preparation technique was electropolishing and anodizing, as before. We are confident in getting better improvement factors for the helix sections. At Argonne, a proton beam has been accelerated. A maximum field strength of about 1.4 MV/m has been measured. The field of one cavity was phase locked to the master oscillator system at a field level of 1 MV/m. Phase wobble was less than 1°.

The possibilities of the application of rf superconductivity thus rapidly expand. We are now in the status of operating prototype accelerators. Though remaining problems have to be solved, I am confident for the future.
Rapid and additional information from the different laboratories is acknowledged.

Finally I would like to list the names of the colloborators of the Karlsruhe group:

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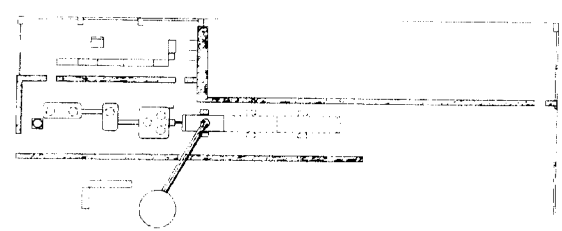

Fig.1. Layout of the Karlsruhe superconducting proton linac.

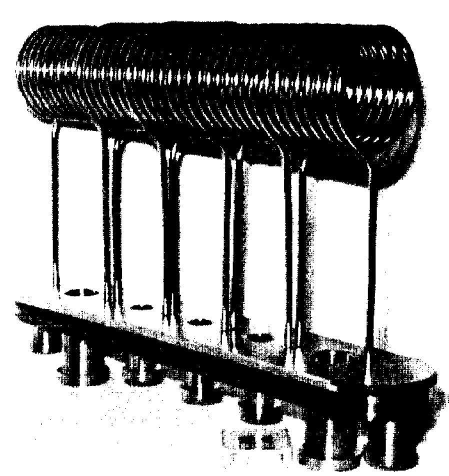

Fig.2. Replaceable Nb helix unit for the first accelerating section.

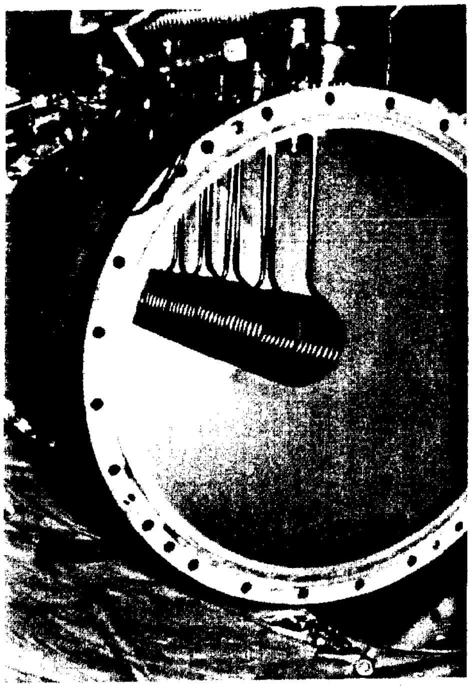

Fig.3. Assembled first accelerator section.

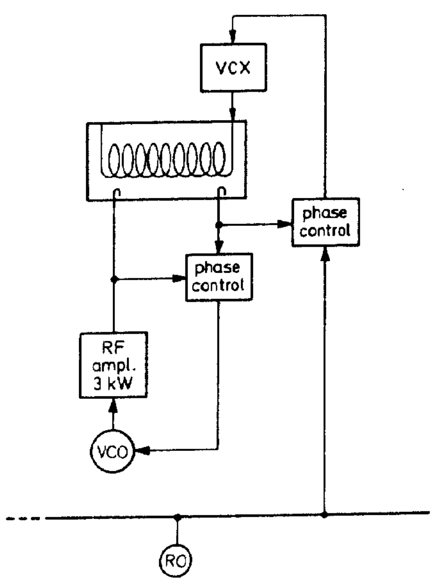

Fig.4. Circuit diagram of the VCO/VCX loop for one helix section.

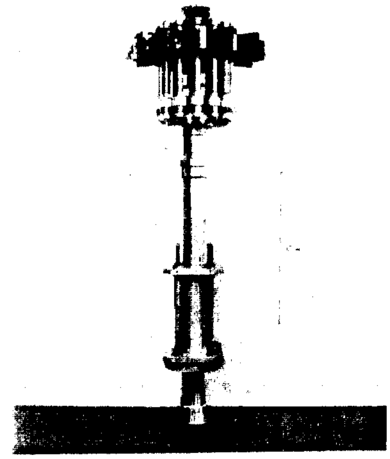

Fig.5. Fast frequency tuner using PIN diodes.

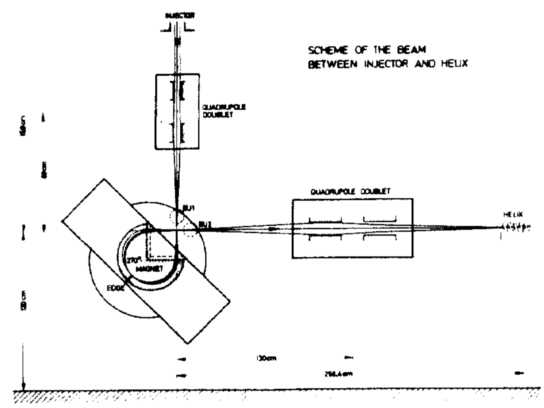

Fig.6. Schematic drawing of the injection system for proton bunches of 22°.

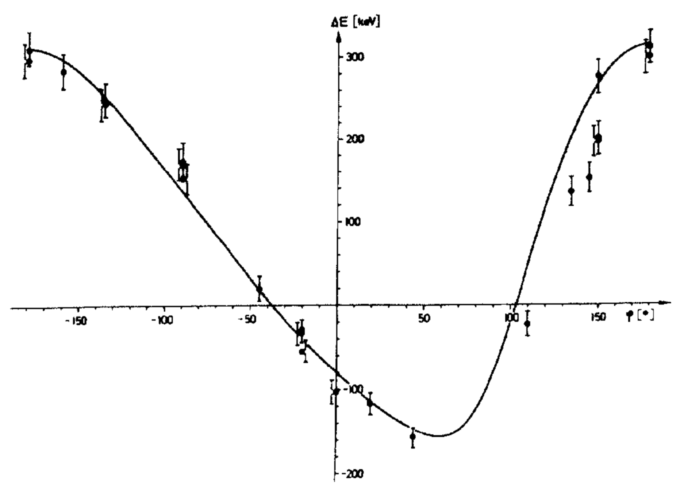

Fig.7. Energy gain of a bunched proton beam as function of particle phase.