LOW-VELOCITY SUPERCONDUCTING ACCELERATING STRUCTURES*

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Introduction

This paper reviews the status of rf superconductivity as applied to low-velocity accelerating structures. While a major amount of effort in rf superconductivity is directed towards high-energy accelerators, the issues associated with heavy-ion accelerators are quite different, and the options and choices available to the accelerator designer are more numerous and varied. Until recently, the rf superconducting technology for heavy-ion accelerators could be considered as being more mature than its counterpart for high-energy accelerators, since a larger number of machines have been operational for a longer time. Figure 1 shows the total accumulated voltage achieved during beam test or operation of superconducting structures [S1]. The solid line represents velocity of higher electron accelerating structures while the dashed line represents low-velocity ion accelerating structures.

The main differences between the two applications come from the fact that heavy-ion accelerators must accelerate efficiently particles which travel at a velocity much smaller than that of light particles, whose velocity changes along accelerator, and also different particles which have different velocity profiles. Heavy-ion superconducting accelerators operate at frequencies which are lower than high-energy superconducting accelerators. Since the rf losses associated with the superconducting state increase roughly quadratically with frequency, the rf superconducting technology did not need to be pushed as far to find useful applications for heavy-ion accelerators.

Previous reviews of low-velocity superconducting structures and accelerators can be found in [B1,B8,D12,K2].

Basic Features of Heavy-Ion Superconducting Structures and Linacs

Heavy-ion superconducting structures are designed to accelerate particles traveling at velocities much smaller than the velocity of light. This implies that unlike velocity of light structures which have a simple surface of revolution geometry operating in the TM_{010} mode, low-velocity structures must be heavily loaded, usually by an internal element. The presence of an internal loading element implies that the design and fabrication of low-velocity structures are substantially more complicated than for velocity of light structures. It also implies that peak surface fields are substantially higher; numbers vary widely among the various structures but typically, at a gradient of 1MV/m, the peak surface electric field ranges from 4 to 6 MV/m,

*This work was performed under the auspices of the U.S. Department of Energy under Contract W-31-109-ENG-38.

A: Stanford
B: Cornell
C: Darmstadt
D: CERN, Cornell, DESY, KEK
E: KEK
F: Karlsruhe
G: Argonne
H: Stony Brook
I: Florida State
J: University of Washington
K: Saclay
L: Argonne PII

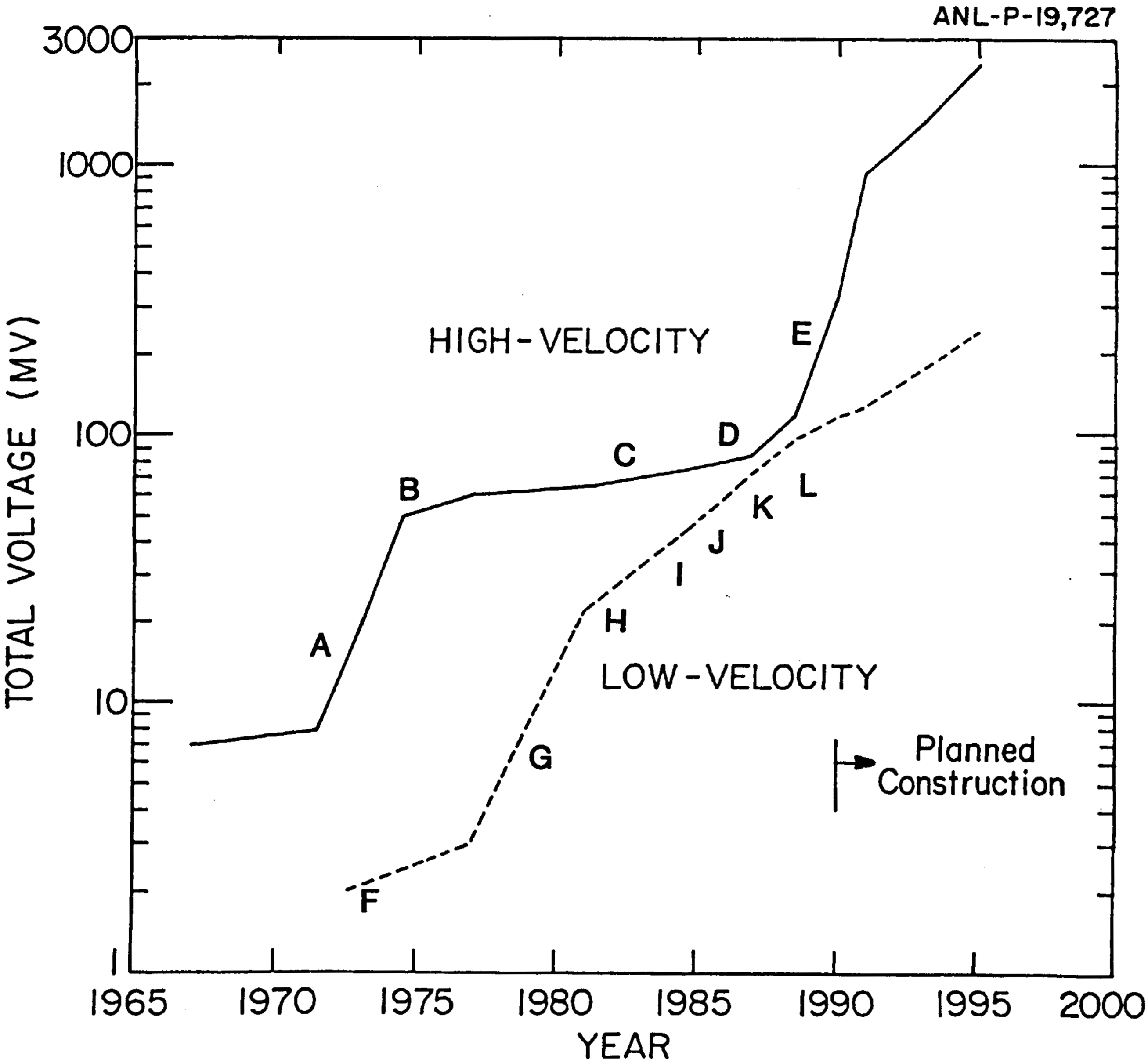

Figure 1. Integrated, accumulative voltage in test and/or operation of superconducting cavities with beam

and the peak surface magnetic field ranges from 60 to 200 gauss. The need for an internal loading element and the requirement that longitudinal dimensions (along the beam line) be much smaller than the wavelength put an upper bound on the frequency of low-velocity structures. Indeed there is a strong correlation between structure β and frequency (see figure 3).

Since, at present, heavy-ion structures are used in the classical, non-relativistic regime, the velocity of the particles changes along the accelerator. This usually means that several structures will be needed in an accelerator, each of them optimized for a particular velocity range. On the other hand, at a particular location in a heavy-ion accelerator, different species will have different velocities and a particular heavy-ion structure must be able to efficiently accelerate particles of different velocities.

Until very recently, all heavy-ion linacs were used as boosters for electrostatic accelerators. Since the electrostatic accelerators were, in most instances, part of existing facilities, the boosters had to be designed to fit in these facilities which explains the sometimes convoluted and less than optimal layout of the resulting tandem-linac systems.

While other accelerating systems exist which can produce high ion beam energies, such as cyclotrons, superconducting linacs offer a range of characteristics which make them attractive for nuclear physics research.

The first characteristic is the ability to preserve the excellent beam quality provided by the tandem accelerator. This is not a trivial matter, since the tandems produce dc beams while the booster requires bunched beams extending no more than a few degrees of rf phase. The currents produced by the tandems are also usually quite low and reduced even more by subsequent stripping, so the bunching process must be done efficiently. The bunching is usually done in two stages: a low frequency normal conducting buncher operating at several harmonics and located at the entrance of the tandem, and a higher frequency often superconducting buncher at the entrance of the linac. A chopper is also usually located between the tandem and the linac. Such bunching systems can compress more than 60 percent of the beam into bunches about 100 ps wide. The beam quality is preserved along the linac by operating it in the longitudinal focusing mode. A rebuncher/debuncher is located at the output of the linac, giving the capability of producing small time spread or small energy spread at the target.

Another important characteristic of superconducting heavy-ion linacs is the use of short, independently-phased accelerating structures. This modularity results in an increased complexity but offers many advantages:

- The velocity profile along the linac can be tailored at will to accommodate a wide range charge to mass ratio
- The capability of the linac is not limited by its "weakest link." A number of resonators can be turned off and still leave the accelerator fully operational although at a smaller output energy or mass range
- A facility can be put to use as soon as a few resonators are installed, well before final completion

- An accelerator can be easily upgraded or retrofitted. For example, its output energy can be increased by adding higher β resonators at the output, or its mass range can be extended toward heavier masses by adding lower β resonators at its input

- The output energy can be easily and rapidly changed by varying the phase of the last few resonators

- Short structures are easier to manufacture than longer ones

Reliability and durability were major concerns in the early days of superconducting boosters. These concerns have now been put to rest. Superconducting structures, both Nb and Pb, have shown good sustained performance in typical accelerator environments, and superconducting boosters have operated reliably and have accumulated more than 50,000 hours of beam on target under minimal supervision.

Design Choices

In a heavy ion accelerator, at constant frequency and gradient, the number of accelerating structures of a given β is proportional to the β of the structure. In other words, for example, twice as many β=0.10 resonators will be required as β=0.05 resonators. This has important consequences on the way a linac, and its structures, are designed. Since few low β resonators are required, their performance in terms of power dissipation is not critical. On the other hand, their design gradient must be achieved otherwise the heaviest ions will not be accelerated sufficiently to be captured by the higher β resonator and the mass range of the accelerator will be reduced. It is therefore advisable to be conservative in the design of the low β section and assume design gradients which are guaranteed to be achieved. The situation for the high β sections is different. The bulk of the refrigeration capacity will be used by the high β resonators and these should be designed to maximize performance (maximum gradient at available power dissipation). Unlike for the low β resonators, failure to achieve design performance with the high β resonators will not result in a reduction of the mass range but in a reduction of the output energy.

Even a rapid survey of the field of superconducting heavy-ion linacs will reveal a wide range in the conceptual designs. This results from a variety of options for the basic design parameters. The choices are being made based upon science, technology, economics, convenience, and maybe even preconceived ideas. Some of these design choices, their consequences, and interrelations will be discussed now.

Structure Geometry

Figure 2 shows all the superconducting structures which have been tested or are under development. They range in frequency from 38 MHz to 850 MHz and in β from less than .01 to .28. A total of 11 types of superconducting cavities have been developed.

Figure 3 shows only the cavities which are in use in an accelerator or which are being developed for use in an accelerator. It is immediately apparent that the number of cavity types is much smaller, being reduced from 11 to 4. With one exception all the Pb cavities have a frequency of 150 MHz or higher while the Nb structures all have frequencies lower than 150 MHz. There are some reasons that explain this segregation (see below), however the situation will become more blurred in the future since higher frequency Nb structures are under development.

A large number of structures have been developed for superconducting linacs:

- Helix [A5,B2,C2,F3,J1,Z1]
- Reentrant [B9,C1]
- Spiral [D1]
- Alvarez [M4]
- Slotted-Irin [M4]
- Split Ring [D2,D13,S2,S4,S12,S13]
- Coaxial-Quarter Wave [B3,B7,D11,S3,S4,S14,T1]
- Half-Wave [D3,D4]
- Interdigital Quarter-Wave [S5,S6]
- Coaxial Half-Wave [D10,D11]
- Spoke [D10,D11]

All of the structures in use today, with the exception of the helix, use quarter-wavelength resonant lines terminated by drift tubes through which the particles travel. A resonator can contain a single resonant line (spiral, quarter-wave, interdigital) or two (split-ring, half-wave) and the lines can be straight (quarter-wave, interdigital, half-wave) or bent (spiral, split-ring).

Resonators using straight inductors have the advantage of greater mechanical stability and lower peak surface magnetic field at the expense of a larger transverse dimension. Resonators using a single drift tube have a wider velocity acceptance while resonators using multiple drift tubes provide a higher energy gain over a small velocity range (at constant frequency and β). The efficiency with which a particular structure accelerates particles of different velocities is represented by its transit time factor. Transit time factors for 2, 3 and 4 gap structures are shown in figure 4 [B1]. Figure 5 shows the energy gain provided by two 150 MHz, β=0.1 structures operating at a peak surface electric field of 16MV/m, one being a 2-gap structure, the other one a 3-gap structure. This figure illustrates the trade-off between wide velocity acceptance and high energy gains. [D14,D15]

At extremely low β, where longitudinal dimensions are so small that several inductors cannot fit inside the structure, the resonant line can be terminated in a multiple drift tube to form an interdigital quarter-wave resonator.

Materials

From the beginning, the two materials of choice have been niobium and lead. The fundamental superconducting properties of Nb are superior to those

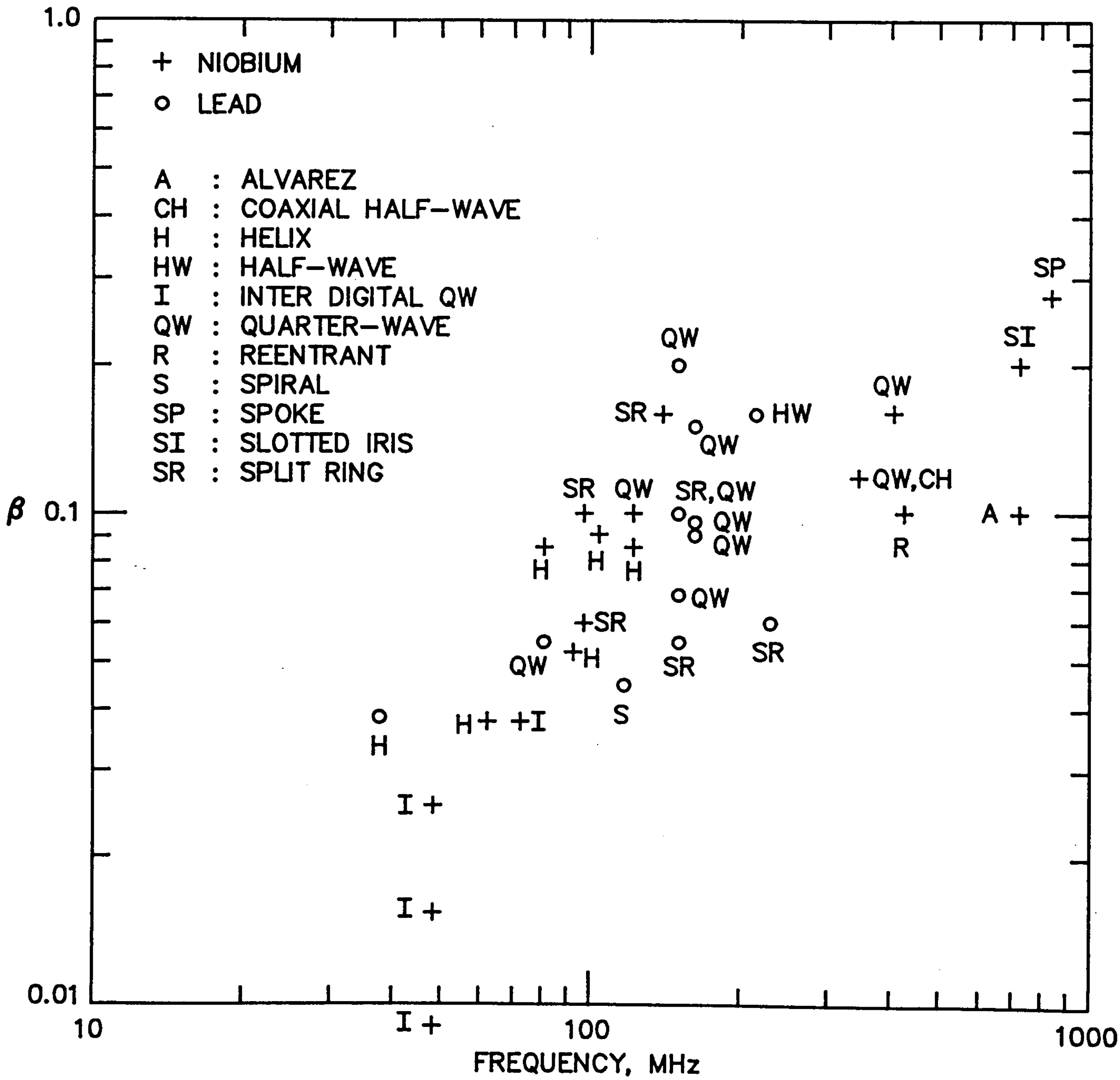

Figure 2: Superconducting Structures which have been Tested or are Under Development

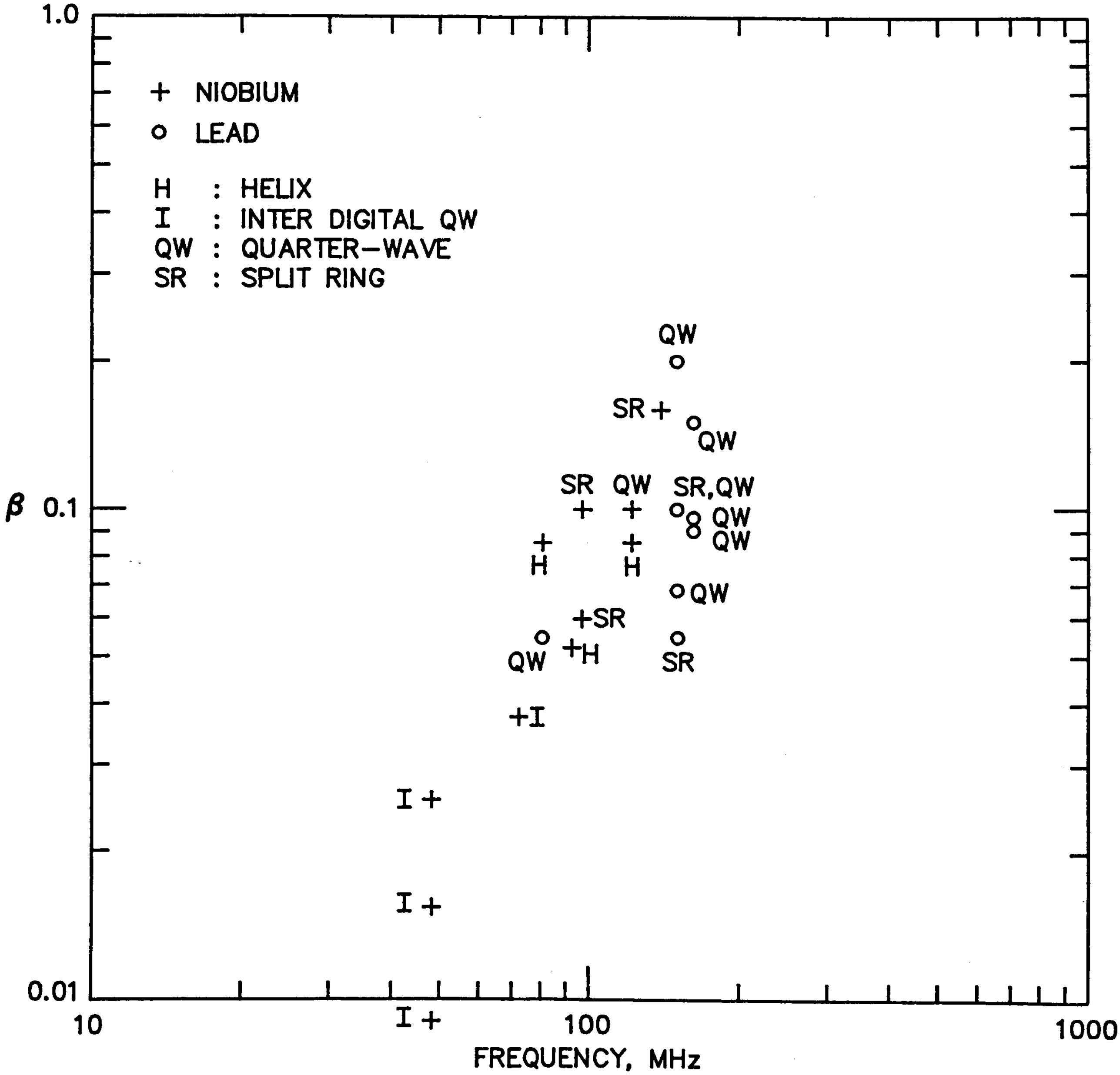

Figure 3: Superconducting Structures in Use or Under Development for Use in an Accelerator

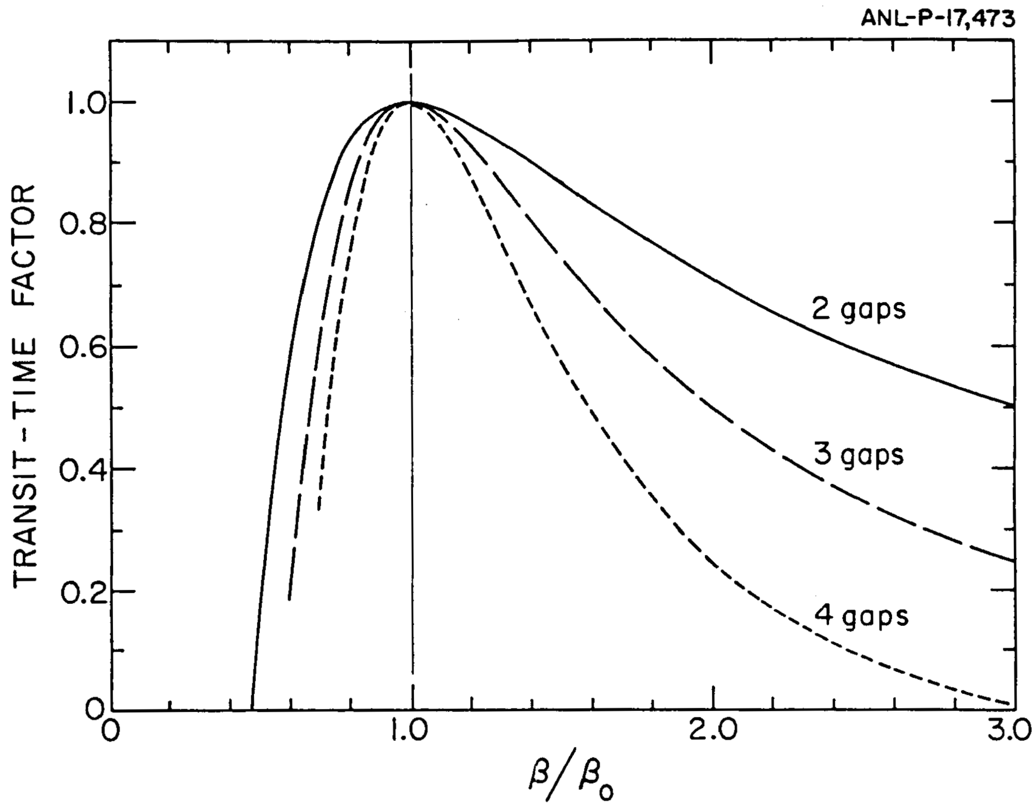

Figure 4. Transit Time Factor for 2, 3 and 4 Gap Structures

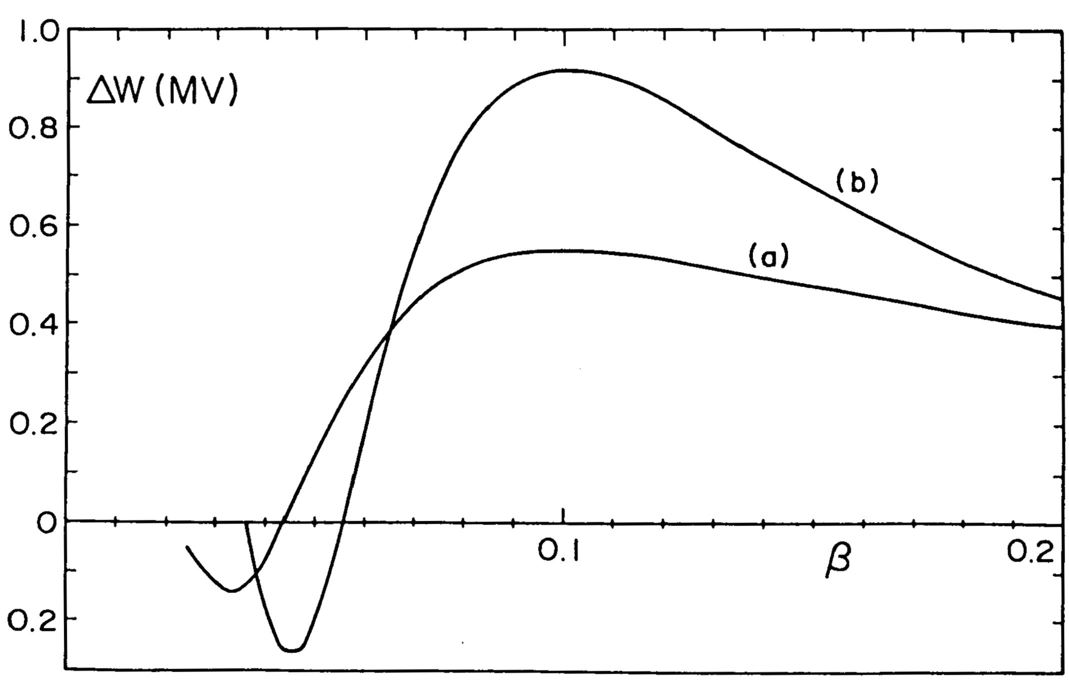

Figure 5. Voltage Gain as a Function of Velocity at a Peak Surface Field of 16 MV/m for Two 150 MHz, β = 0.1 Structures: (a) 2-gap Structure, (b) 3-gap Structure

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of Pb; its transition temperature and critical field are higher, its surface resistance is lower. This translates into a lower power dissipation to achieve a given accelerating field thus reducing operating costs; Nb resonators, on the other hand, are more expensive to manufacture.

Both Pb and Nb resonators still operate below the theoretical limits and their performance is rarely limited by fundamental superconducting properties.

Pb resonators are obtained by electrodeposition of a few microns of Pb onto a high-thermal conductivity Cu structure [D5,D6]. The Cu base acts as a stabilization element against magnetic-thermal breakdown by carrying away the heat generated at local "hot" spots. Improved thermal stability of Nb resonators has been achieved by the use of high thermal conductivity Nb and explosive bonding of Nb onto Cu [S7]. Attempts are being made at sputtering thin layers of Nb on Cu [M1]; however, because of the complicated geometry of low-velocity structures, success has not yet been achieved.

Frequency

The accelerating structures used in superconducting heavy-ion linacs have lower resonant frequencies than those used in high-energy superconducting accelerators, typically between 50 and 200 MHz.

The advantages of lower frequencies are:

- The beam bunches occupy a smaller rf phase angle
- Fewer resonators are required to provide the same energy gain
- In principle, power dissipation in the cavities is smaller

The advantages of higher frequencies are:

- The resonators and cryostats are smaller
- Higher frequency resonators are easier to phase stabilize
- High frequency resonators seem to achieve higher gradients.

Nb structures often have resonant frequencies which are lower than those of Pb structures. This is party due to historical reasons and partly due to the fact the Pb enters the residual resistance requirements at higher frequency than Nb does.

Phase Control

Phase control which once was thought to be a major drawback of heavy-ion superconducting accelerators is not an issue anymore with today's cavity designs, frequencies, and achievable gradients. On the other hand, if a way was found to dramatically increase the achievable gradients, then phase control could become an issue again, especially for the lower frequency structures.

Phase stabilization is usually accomplished in one of two ways. One way is by using an external voltage-controlled reactance which can be either electrically coupled or decoupled to the resonators [B10,D7,D16,H1,S15]. By adjusting the duty cycle between the two states, the average phase of the rf field in the resonator can be backed to an external reference. This method is used in large, less stable structures. The other method of phase stabilization is by negative phase feedback where no attempt is being made at controlling the resonator frequency [B11,D8,D9]. Instead, the resonator is operated in a self-exited loop, its loaded bandwidth is artificially broadened by overcoupling and the loop oscillation frequency is controlled. This method is simpler, in principle, than the previous one but limited to the smaller, more stable structures.

Focusing

Focusing in superconducting linacs is usually achieved either by room temperature quadrupoles located between the cryostats or by superconducting solenoids located inside the cryostats. The first solution results in a larger number of simpler cryostats while the second results in a smaller number of more complicated cryostats.

Status of Superconducting Booster Projects

Argonne National Laboratory [A2,M2,B4]

The ANL superconducting linac was the first and is still the largest of the existing machines. First beam was delivered in 1978, the booster was dedicated in 1982 and ATLAS in 1985. The whole machine uses Nb split-ring resonators: 11 of β=.06 at 97 MHz, 22 of β=0.1 at 97 MHz and 9 of β=0.16 at 145 MHz. Focusing is accomplished by superconducting solenoids located inside the cryostats after every pair of resonators. Phase stabilization is accomplished by voltage-controlled reactances. A positive ion injector consisting of an ECR source and a very low velocity linac is under construction as a replacement for the tandem.

SUNY Stony Brook [N1,S8]

The Stony Brook machine, which was dedicated in 1983 also uses split-ring resonators but made of Pb on Cu. It consists of 16, β=0.55, resonators in four cryostats and 24, β=0.10, resonators in eight cryostats. Focusing is done by room temperature quadrupoles located between the cryostats. Phase stabilization is accomplished by negative phase feedback.

The performance of this machine has been limited by two factors. The full refrigeration capability of the refrigerator was not delivered to the cryostats, but a fraction of it was lost in the distribution system. Most of the sources of additional loss have now been identified. The low β resonators could not be operated at design field because of excessive mechanical vibrations; these resonators are being replaced by quarter-wave resonators.

Weizmann Institute [B5]

The Weizmann Institute booster project saw the first use of the quarter-wave resonators. It was a small machine consisting of a single cryostat of four Pb/Cu resonators (β=.095, 160 MHz). There are no plans for extension.

University of Washington [A3,S9]

This machine, operational since September 1987, was the first to make large scale use of Pb/Cu quarter-wave resonators: 24 of β=0.1 in six cryostats and 12 of β=0.2 in six cryostats, all operating at 150 MHz. It is designed to produce β=0.3 protons, which is, at present, the highest velocity beam produced by a superconducting booster.

Florida State [F1,M3]

Dedicated in 1987, this machine uses ANL resonators (13 Nb split-ring cavities). The cryostats have been redesigned so the resonators are positioned upside down compared to their position in the ANL cryostats.

Saclay [C2,R1]

The Saclay booster is the first and only machine to use helices. All resonators have β=.085, with 16 resonating at 81 MHz and 34 at 135 MHz. Half of the accelerator has been operational since December 1987, and the whole machine became operational in March 1989.

Phase stabilization is accomplished by multistep VCX located outside the cryostats. The cavities are immersed in liquid helium, and the helium is forced through the helix tubing. This machine is the only example of low-velocity structures immersed in liquid.

Kansas State [G1]

The unique feature of this facility is that it is designed to be used as a decelerator. Ions are stripped to a high charge state either at the output of the tandem or after the first few resonators and then decelerated by the rest of the linac. It uses Argonne's Nb split-ring resonators (5 of β=.06 and 5 of β=0.1).

Daresbury [A4]

This machine started as an Oxford booster made from 10 Pb/Cu split-ring resonators, β=0.10, 150 MHz. The hardware was transferred from Oxford to Daresbury in 1988 and is under installation. The possibility of adding other resonators to increase the capability of the facility is under study.

Japanese Atomic Energy Research Institute [T1]

This machine, which is in the early construction stage, will make the first use of the Nb quarter-wave resonators. Tests of prototypes have produced fields of 6 MV/m at a power dissipation of 4 W.

Present funding calls for four cryostats of four resonators each; future plans call for six additional cryostats.

Legnaro [F2]

A large project with the goal of adding 36 MV equivalent to a 16-MV tandem. It will make use of 93 Pb/Cu quarter-wave resonators:

24 cavities of β=0.55 at 80 MHz
48 cavities of β=0.09 at 160 MHz
21 cavities of β=0.15 at 160 MHz

Bombay [K1]

Still in the planning stage, this project calls for 11 cryostats of four 150-MHz Pb/Cu quarter-wave resonators injected from a 14 UD pelletron.

Sao Paulo [S11]

First phase calls for 14 Nb split-ring resonators of Argonne's design located in two cryostats, plus a buncher and a rebuncher.

ANU, Canberra [W1]

This project originally called for 40 Pb/Cu quarter-wave resonators. All efforts, recently, have been directed toward sputtering of Nb onto Cu quarter-wave structures.

Munich [T2,T3]

This machine is unlike every one previously mentioned, since it is not a linac but a separated orbit cyclotron which includes six cavities operating at 170 MHz. The cavities are made of Cu and plated with a Pb-Sn alloy.

Recent Developments and Future Prospects

Following the pioneering successes of the Argonne and Stony Brook accelerators, the last few years have seen a large increase in the number of superconducting boosters which have come into operation or which are under construction. The technology, however, has not remained static, and advances are still being made.

Some of the limitations of existing tandem-linac systems, most notably the available ion mass range and beam currents, are due not to the superconducting booster but to the electrostatic injector. The major advances which have taken place recently have been in the area of replacement of existing negative-ion source--tandem combinations by ECR ion source--superconducting injector linac combinations. An ECR source located on a high voltage platform can produce ions with high charge states and sufficient velocity to be injected directly into a superconducting linac. This approach, which has been recently demonstrated at Argonne [B4], has required the development of a new class of low-frequency (~50 MHz), low-velocity (~0.1 c) superconducting structures [S5,S6,S10]. Another approach, which is being investigated at Stony Brook and still is in the early development stage, is an ECR source-superconducting RFQ combination [B6].

A completely different application of superconducting heavy-ion linacs, which is also under investigation, is for the acceleration of high-current ion beams [D10]. The issues which will have to be addressed are quite different from those related to boosters. For example, in the case of high-current beams, the ability to produce high, CW accelerating fields is more important than power efficiency. If such high-current superconducting ion accelerators come into existence, they will be quite different in their design philosophy from the superconducting boosters which are now in existence.

The superconducting rf technology for ion accelerators is now established, widespread, and well proven. At the same time that the number of construction projects is increasing, advances are being made into new areas of application of the technology.

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