REVIEW OF ELECTROSTATIC ACCELERATORS AND LINAC BOOSTERS

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Abstract

The brief review concentrates on large tandem accelerators and superconducting linac boosters. An outline of the performance of tandems is given. The limiting performance of accelerator tubes is discussed together with some recent steps taken to improve voltage performance. The effects of voltage transients is mentioned and a brief outline of the new Vivitron accelerator under construction at Strasbourg given. Some general features of tandem-linac booster system are discussed and a summary made of existing and planned facilities. The resonant structures in current use are described together with some developments.

Introduction

It will be impossible to review the whole field of electrostatic accelerators ranging from small Cockroft-Walton generators operating at some hundreds of kV to the largest tandem Van de Graaffs with voltages up to 35 MV, as currently in operation or under development, within the time available. Rather an attempt will be made to illustrate the strengths and importances of such accelerators and indicate their limiting features and the efforts currently in progress to minimise the effects of these weaknesses. I will do this by concentrating on the largest planned and operational facilities.

An increasingly popular way of upgrading the energy capability of tandem facilities has been the addition of linac boosters which are now predominantly based on superconducting resonating structures. These boosters not only preserve the inherent versatility and beam quality of tandem accelerators but enable their low longitudinal emittances to be exploited in producing bunched beams of some 150 ps duration. A brief summary of existing and proposed facilities will be given.

Large Tandem Accelerators

In Figure 1 the energy performance of the largest operational or planned tandems are illustrated including the 20 MV tandem at Daresbury Laboratory and the ESTU at Yale University, the 25 MV NEC accelerator at Oak Ridge National Laboratory and the 35 MV Vivitron accelerator under construction at CRN, Strasbourg. It is clear that in comparison with other acceleration systems energy alone is not an over-riding criterion for the continued existence of the tandem. The energy regime is however ideally matched to the requirements of low energy nuclear structure research where the other advantages of tandem accelerators play leading roles.

Probably the single most important advance for tandems has been the developments by Middleton, Alton[1,2] and others of versatile negative ion sources. Now, with few exceptions, most ion species in the periodic table can be produced as negative ions in either the elemental or molecular form. This is illustrated in Table 1 by the beams accelerated to date by the Daresbury tandem which not only include low natural abundance species such as ^{48}Ca, radioactive beams such as tritium and ^{14}C but also polarised beams of ^{6}Li, ^{7}Li and ^{23}Na. The centre terminal stripper plays a crucial role in determining the properties of beams from tandems. Stripping of the negative ion in the centre terminal preserves the "purity" of beams injected as molecules by effectively "decoupling" the unwanted element from the element of interest and, in the case of polarised ions, complete electronic stripping of ^{6}Li and ^{7}Li and stripping to the 9^{+} charge state in the case of ^{23}Na minimises depolarising effects. The stripper also plays an important role in determining the quality of the output beam. In general the effects of energy loss straggling, small angle scattering and foil non-uniformity are the deciding

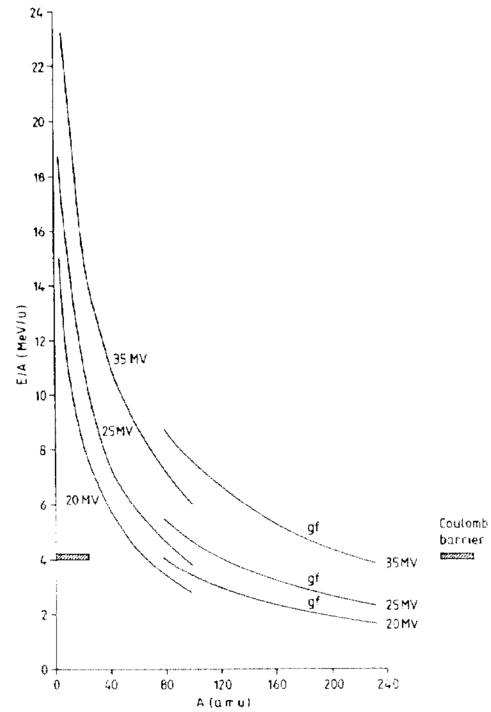

Fig. 1. The output beam energy from tandem accelerators operating at 20 MV, 25 MV and 35 MV. Use of a terminal gas stripper and a second foil stripper has been assumed for A > 80.

factors for the transverse and longitudinal phase space and energy resolution of heavy ion beams from a tandem. Typical values are $\varepsilon_{tr} \sim 3\pi$ mrad, $\varepsilon_{long} \sim 15\pi$ keV ns and $\Delta E/E \sim 5 \times 10^{-4}$ which when coupled with easy energy variability and DC beam structure make tandem accelerators not only precision tools for nuclear structure research but amenable to many forms of post accelerator boosters.

Table 1

^{1}H	^{26}Aℓ	^{50}Ti	^{76}Se
^{2}D	^{27}Aℓ	^{50}Cr	^{77}Se
^{3}T	^{28}Si	^{52}Cr	^{78}Se
^{4}He	^{29}Si	^{53}Cr	^{80}Se
^{6}Li	^{30}Si	^{51}V	^{82}Se
^{7}Li	^{31}P	^{54}Fe	^{79}Br
^{9}Be	^{32}S	^{56}Fe	^{81}Br
^{10}B	^{33}S	^{58}Ni	^{90}Zr
^{11}B	^{34}S	^{60}Ni	^{92}Zr
^{12}C	^{36}S	^{61}Ni	^{92}Mo
^{14}C	^{35}Cℓ	^{62}Ni	^{98}Mo
^{14}N	^{36}Cℓ	^{64}Ni	^{100}Mo
^{16}O	^{37}Cℓ	^{63}Cu	^{127}I
^{17}O	^{40}Ca	^{64}Zn	^{128}Ba
^{18}O	^{44}Ca	^{66}Zn	^{174}Yb
^{19}F	^{48}Ca	^{72}Ge	^{181}Ta
^{23}Na	^{45}Sc	^{74}Ge	^{192}Os
^{24}Mg	^{46}Ti	^{76}Ge	^{197}Au
^{25}Mg	^{47}Ti	^{74}Se	^{209}Bi
^{26}Mg	^{48}Ti	^{75}Se	

At present there are three electrostatic accelerators operating at voltages of 20 MV or over; the 20 MV tandem at Daresbury Laboratory, UK, which has been operational since 1983, is shown in Fig. 2, the 25 MV NEC tandem at Oak Ridge National Laboratory, USA, operational since 1982 is shown in Fig. 3, whilst the 20 MV ESTU at Yale University commenced operation in 1989 and has already operated with beam at a voltage of 20.5 MV. These accelerators are reliable and in the case of both Oak Ridge and Daresbury operate with over 4500 hours of beam on target per annum.

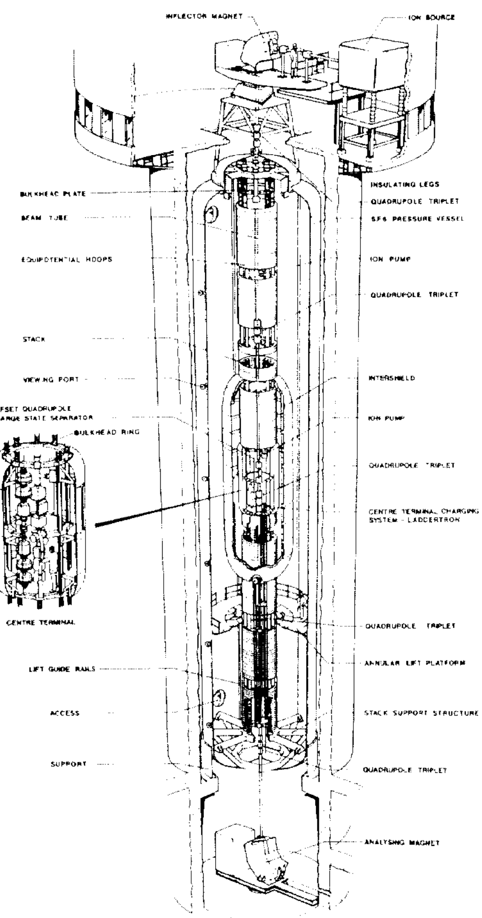

Fig. 2. The Daresbury Laboratory Tandem.

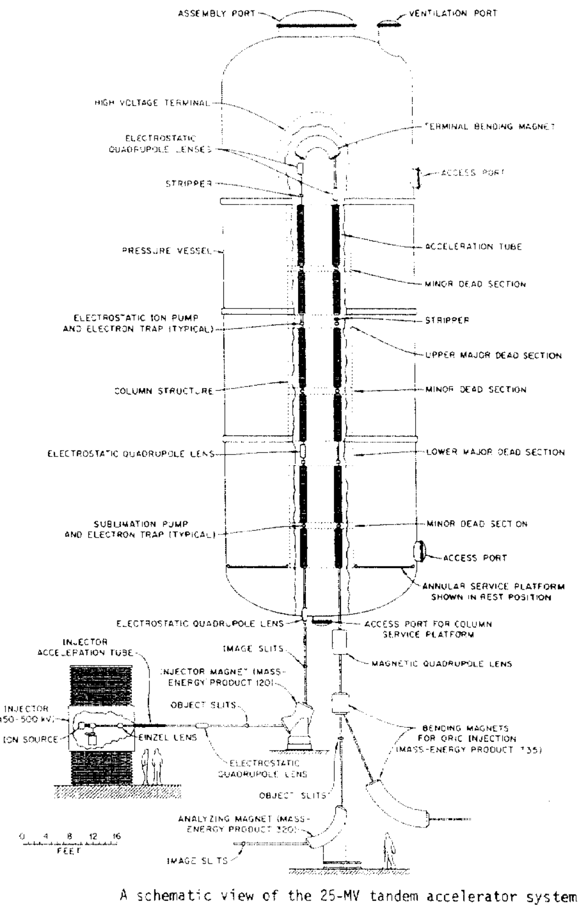

Fig. 3. The Oak Ridge National Laboratory NEC Tandem.

Voltage Performance

Clearly an important parameter for electrostatic accelerators is voltage capability. It is true that in most instances the voltage level achieved by electrostatic accelerators without accelerator tubes have met or even exceeded their electrostatic design voltage which on average exceeds the final voltage capability by up to 45% when the accelerator tubes are installed. It is still true therefore that the limiting factor which governs voltage performance is the active electric field capabilities of accelerator tubes. The problem presented by high gradient long accelerator tubes is the large number of possible discharge paths. A general summary of these is illustrated in Fig. 4. Tube construction generally falls into two categories:

(a) stainless steel electrodes glued to borosilicate glass insulators as, for instance, manufactured by HVEC and Dowlish, and
(b) titanium electrodes diffusion bonded to high alumina ceramic as manufactured by NEC and in-house at Daresbury.

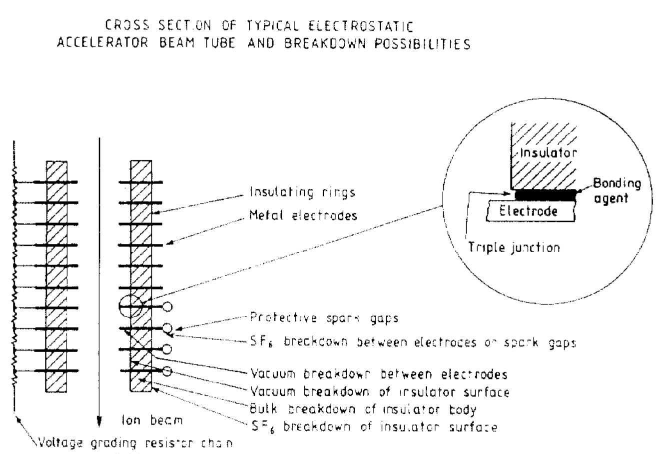

Fig. 4. Various accelerator tube breakdown possibilities.

The main contribution to performance limitation however is the behaviour within the vacuum gap. An excellent review of this topic has been given by Joy[3] and reference therein, and it would be inappropriate to review all the possible breakdown and emission mechanisms here. However, it is important to recognise that the emission processes occur in an extended system. The designs of accelerator tubes have therefore been aimed at localising the trajectories of electrons and ions produced in the emission processes so as to minimise their gain in energy and hence subsequent amplification of the process once initiated.

This localisation in general has been achieved by two successful methods, viz the inclined field tube in which the accelerating field is at an alternating angle to the beam axis, thereby imparting a tranverse force on the emitted particles; and axial field modulation which creates a transverse force by the application of periodic electrostatic lenses which deflect the low energy ions and electrons produced in the emission process. These overcome the so-called long tube effect. The limiting factor is then the electric field achievable over the accelerator tube and the accelerator voltage performance is just dependent on the total length of accelerator tube. Figure 5 summarises the present status of achievable active tube gradients for several tandem accelerators. As a general statement one can see from this figure that for large accelerators reliable operation can be achieved with fields of up to 2 MV/M. With this in mind, it is clearly within the interests of the designer to ensure that the column length from terminal to ground is as efficiently filled with actual accelerator tube as possible with a minimum of "dead" length.

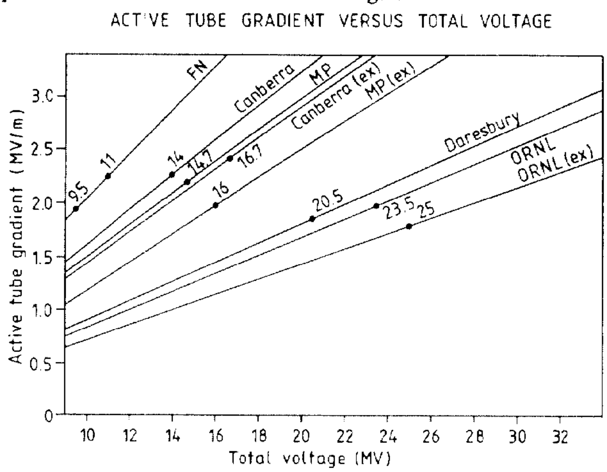

Fig. 5. A summary of active accelerator tube gradients.

Most of the recent advances in voltage performance has been achieved by more efficient use of column length by increasing the effective length of accelerator tube. This has been particularly successful at Oak Ridge where installation of a new so-called compressed geometry tube with improved suppression has effectively increased the active tube length by 17%. This has resulted in a proportional increase in voltage performance as indicated in Fig. 6. Improvements in voltage performance through effectively lengthening live accelerator tube length has been achieved at several other laboratories with particularly impressive results being achieved at Canberra where the voltage of a 14 MV machine was increased to 16.7 MV.

Voltage Discharge

No matter how good the voltage performance of the electrostatic accelerator discharges will occur. The stored energy in a tandem varies approximately as the cube of the design voltage so considerable energy can be liberated in a very short timescale in a discharge. In the case of the Daresbury machine for instance the stored energy is approximately 10^5 Joules at 20 MV.

The electrical behaviour during a discharge is complicated and difficult to calculate but attempts[5] have been made using a variety of models to determine the transient voltages. The results of one such calculation are shown in Fig. 7 which indicate that large overvoltages can occur along a column in timescales of the order of 0.1 μs. This implies that particular attention must be given to minimising the possibility of damage to accelerator tube and other components. This entails conditioning the accelerator tube electrode surfaces to minimise the probability of internal arcing and protection by appropriate spark gaps weak enough to fire before insulator breakdown or a vacuum discharge occurs.

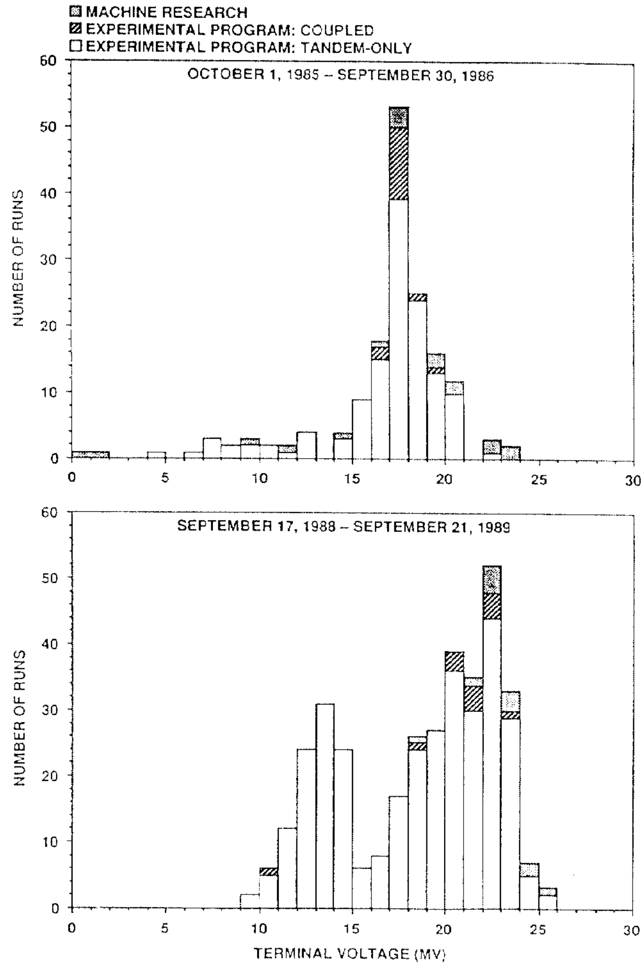

Fig. 6. The voltage performance of the Oak Ridge Tandem before and after installation of the compressed geometry tubes.

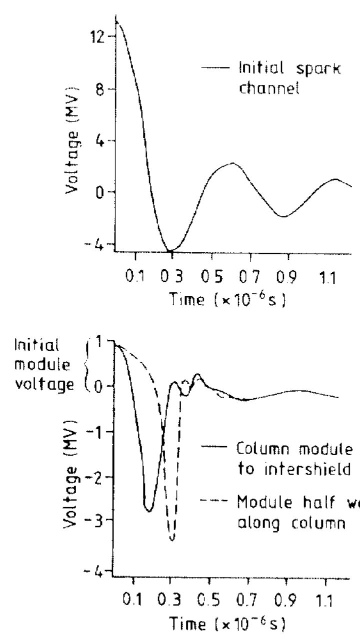

Fig. 7. Calculated transient waveforms for an intershield to tank spark in the Daresbury Tandem.

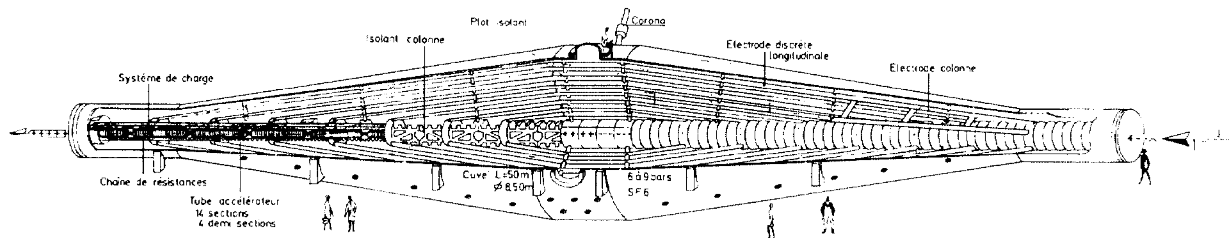

Fig. 8. The Vivitron Accelerator at CRN Strasbourg.

<u>The Vivitron</u>

A radical new approach to electrostatic accelerator design has been taken by CRN Strasbourg in the construction of their 35 MV Vivitron accelerator. They have directly addressed the problem that most of the stored energy in conventional tandems is located at the terminal and column structure close to the components most vulnerable to damage during discharge. By means of a system of discrete electrodes, shown in Fig. 8, they not only make a more uniform and reduced radial field which allows a reduction in tank diameter but also, and importantly, redistribute the stored energy more uniformly through the whole volume of the accelerator thus avoiding the concentration near the column. The development of new insulating posts by Cooke at MIT has enabled the column and discrete electrode system to be supported radially and hence a horizontal structure can be constructed. The active gradient on the accelerator tube has been chosen conservatively at 1.72 MV/M. Voltage tests on the accelerator are anticipated in 1990 and the whole community awaits with interest the results of this new approach.

<u>Tandem Linac Boosters</u>

The versatility of tandem accelerators is illustrated by the large range of post accelerator systems which have been adopted throughout the world. For example, tandems are used to inject synchrotrons, heavy ion storage rings, warm and superconducting cyclotrons and warm and superconducting linacs. The increasingly popular choice of booster accelerator however is the superconducting linac. The reason for this choice is clear. Since the construction of the first superconducting linac at Argonne National Laboratory, which began operation in 1978, the technology for resonator construction has become reasonably well established. Furthermore, an appropriately designed linac preserves all the advantages of energy and beam variability and beam quality of a tandem accelerator whilst its intrinsic modular nature lends itself to a staged development and expansion.

The essential components of a tandem-linac accelerator complex are shown in Fig. 9. They consist of a two stage bunching system - a low energy pre-tandem buncher and a post tandem superbuncher which are coupled with a phase stabilisation circuit to correct for ion transit time variations through the tandem due to accelerator tube gradient variations. This overall system matches the tandem longitudinal phase space to the linac acceptance. Since the linacs are operated in a phase focusing mode and the maximum output energy is required, they are usually followed by a rebuncher/debuncher. This transforms the output longitudinal phase space ellipse to the appropriate requirements of the experimenter either to ensure beam bunches with a small time width of the order of some 100-200 ps or a DC beam with a low energy spread of some $\Delta E/E \sim 5 \times 10^{-4}$.

Table 2 summarised some essential parameters of existing and proposed linacs used as boosters for electrostatic accelerators. The reader is referred to the comprehensive review of heavy ion linac boosters carried out by Ben-Zvi[6] for further details. There are three basic resonator structures in current use in superconducting linacs, viz the helix resonator as used successfully at Saclay and the more ubiquitous split loop and quarter wave resonators. General examples of these three structures are shown in Fig. 10. The particular disadvantage of

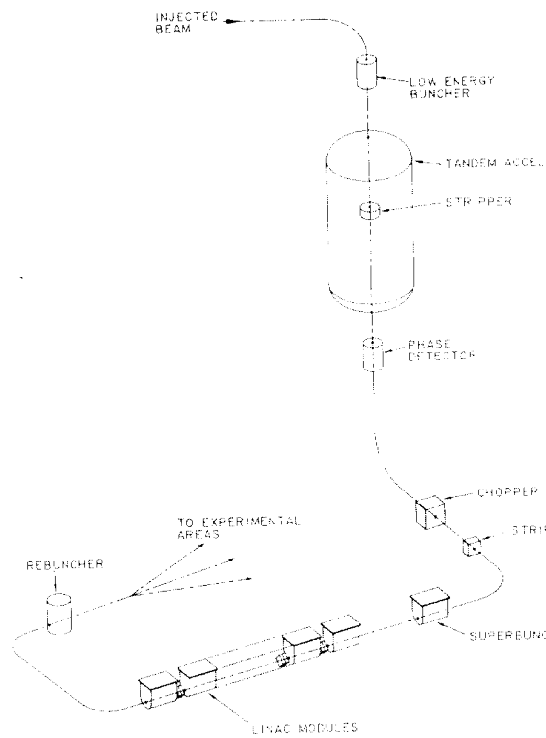

Fig. 9. A generalised layout of a tandem plus booster linac system.

Table 2

Laboratory	Tandem Voltage (MV)	Linac Voltage (MV)	Resonators (b)
Argonne	9	33	Nb SLR
Daresbury	20	5	Pb SLR
Florida State	9	9.7	Nb SLR
J.A.E.R.I. (a)	18	30	Nb QWR
Kansas State	6	9	Nb SLR
Legnaro (a)	16	36	Pb QWR
MPI Heidelberg	12	25	Cu SP + SLR Warm
NBI Copenhagen	9	7.2	Cu IH Warm
Saclay	9	16	Nb HX
Stony Brook	9	13	Pb SLR + QWR
TU Munich	13	9	Cu IH Warm
Washington	9	20	Pb QWR
Weizmann Inst.	13	1.9	Pb QWR

(a) Under construction
(b) SLR = Split Loop Resonator
QWR = Quarter Wave Resonator
HX = Helix Resonator
SP = Spiral Resonator
IH = Interdigital H Resonator

the helix is the fact that it is prone to mechanical vibration, the quarter wave resonator, being a two gap structure, has a wide velocity acceptance and is mechanically more stable than the split loop resonator which, being a three gap structure, has a somewhat narrower velocity acceptance but has a larger energy gain for the same electric field and structure. The superconducting materials in use are still niobium or lead plated copper, although lead-tin alloy has been used at Stony Brook. The choice of structure or superconducting material is never clear as can be seen from the wide range in use. It is based on the range of masses to be accelerated, coupled with the injection energy of the tandem, local manufacturing capability and, perhaps, prejudice.

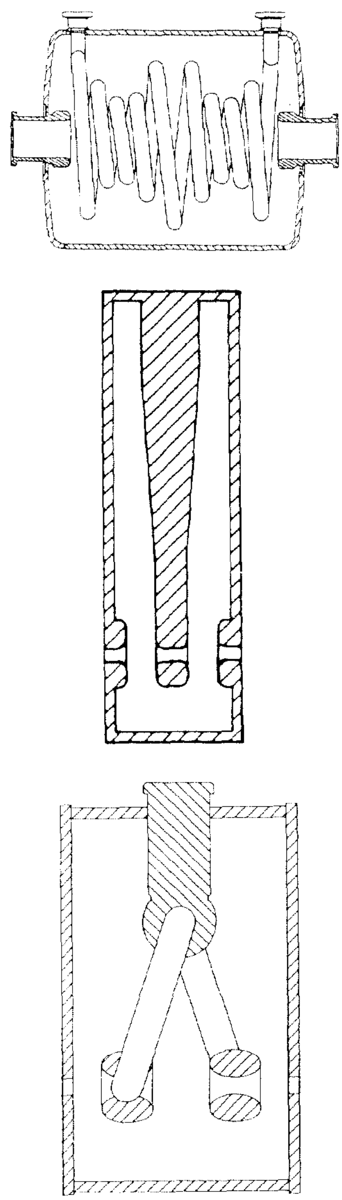

Fig. 10. Generalised drawings of the helix, quarter wave and split loop resonators in current use in heavy ion superconducting linac boosters.

The effective accelerating fields vary from some 2.5 MV/M for lead plated copper up to 6 MV/M demonstrated for the prototype niobium quarter wave developed by Takeuchi[7]. This prototype will be utilised in the linac presently under construction at J.A.E.R.I. in Japan. In Europe, a major facility is presently under construction at INFN Legnaro in Italy, based on lead plated quarter wave resonators which will accelerate uranium beams above the Coulomb barrier.

Generally, it must be stated that it is now clear that superconducting heavy ion linacs, which up until now have only been utilised as booster accelerators, have come of age and are weaning themselves of their tandem injectors. This has been brought about by the advent of ECR ion sources which now produce intense beams of high charge state heavy ions. An ECR source on a high voltage platform coupled with low velocity resonant structures can therefore replace a tandem as an injector to existing linacs. This development has taken place at Argonne National Laboratory with the successful construction of niobium resonators with as low a β as $\beta = 0.009$ based on an interdigital H structure. Meanwhile superconducting radio frequency quadrupoles are being developed by Ben-Zvi at SUNY Stony Brook for a similar purpose. The future of superconducting heavy ion linacs is therefore assured becoming stand-alone accelerators in their own right.

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