RECENT DEVELOPMENTS IN RF SUPERCONDUCTIVITY FOR LINAC STRUCTURES

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Abstract: The status of superconducting linear accelerators for heavy ions and for electrons is reviewed. New types of cavities for heavy ion acceleration have been developed and fields of 3-4 MV/m can be reached routinely. They will extend the velocity range towards lower and higher values and allow new applications. Multicell cavities for electron acceleration now reach field levels of 5-10 MV/m and Q_o values of a few 10^9 in a reliable way and regular production by industry can be envisaged. Latest results obtained with Nb-coated Cu-cavities and with Nb_3SN cavities are given. Some new developments for cryostats, tuners and couplers are shortly described.

Introduction

In the beginning of the 70's the first operation of the Stanford recyclotron[1] inaugurated the area of superconducting s.c. linear accelerators for electrons. The first operation of the Argonne Heavy Ion Postaccelerator[2] in 1978 and of the Stony Brook Heavy-Ion Linac[3] in 1983 pathed the way for acceleration of heavy ions by s.c. cavities. These two machines have ever since been operated on a routine basis and many thousands hours of operation have been accumulated and have confirmed the reliability of s.c. accelerator systems. In the late 70's the use of s.c. cavities in storage rings was considered and has led to a series of tests with s.c. cavities in existing storage rings. The outcome of these tests has been recently reviewed by R. Sundelin[4] and H. Piel[5,6] and confirms fully the hopes placed in the new technology. The latest tests have yielded average acceleration fields of 4 MV/m. The measured instability thresholds indicate that the higher order mode (hom) dampings which can be achieved are adequate for multi-turn instabilities in the machines for which they were developed. Some s.c. systems were operated by using standard control and regulation systems taken over from Cu-cavity systems. Since the latest review two more results have been obtained concerning the long term behaviour in a storage ring environment. A 1 GHz, 9-cell cavity has been kept at low temperature inside the PETRA storage ring at DESY[7] and a 500 MHz, 3-cell cavity has been connected to the vacuum system of the TRISTAN accumulator ring at KEK[8]. After a period of 6 months no degradation in accelerating fields and quality factors was observed.

These promising results have already led three laboratories to make definite plans for application of s.c. cavities on a large scale. At CERN[9] s.c. cavities at 350 MHz will be used for upgrading LEP energies beyond 50 GeV, at DESY[7] 500 MHz s.c. cavities will supplement the n.c. cavities for the HERA electron ring and at KEK[10] 500 MHz s.c. cavities are planned for installation in TRISTAN.

During the last years only one new linear accelerator for electrons has been under construction, the Darmstadt/Wuppertal recyclotron which is planned for an energy of 130 MeV. This accelerator uses 3 GHz, 20 cell cavities which have been fabricated by industry. A system test with one 5-cell and two 20-cell structures is under way[11].

Very recently a much larger linear accelerator project has been started at SURA, Newport News[12]. The Continuous Electron Beam Accelerator Facility (CEBAF) will be a high intensity, CW electron accelerator for nuclear physics. A particle energy of 0.5 to 4 GeV is at present considered with a beam current of 200 μA and a 100% duty cycle. This accelerator will be equipped with s.c. cavities at 1.5 GHz of a type developed for storage ring applications at Cornell University[13].

S.c. cavities are also considered for free electron lasers, mainly because of the high quality beams which can be expected with these cavities[14].

Finally, the possible application of s.c. cavities in large linear colliders should be mentioned[15,16]. These machines will ask in nearly all aspects for a tremendous extrapolation of present day accelerators. Cavity performances will have to be brought up from the present ~ 10 MV/m level in multicell cavities to at least 25 MV/m if not 50 MV/m. The corresponding Q-values will have to reach 5×10^{10} or even 10^{11} in order to keep the cost and power of cryogenic systems to a tolerable level. The requirements for economic fabrication methods of cavities, cryostats and all auxiliary items will ask for mass-production techniques not yet applied to accelerator construction.

The use of s.c. cavities as "drive" linacs[17,18] for very large colliders is also considered. The performances of low frequency linacs (350-500 MHz) considered today for storage rings would already be interesting for this kind of application.

In the following we present some recent developments and results and it will be tried to summarise briefly the possibilities which are at present available for the construction of s.c. linacs.

Superconducting low β structures for heavy ion acceleration

Work on s.c. postaccelerators is going on at more than 10 laboratories[19] and in the last 3 years this field has shown a remarkable activity. Several new cavity types have been developed and tested and progress in fabrication and preparation techniques has been substantial. The very successful operation of s.c. heavy ion linacs at Argonne and Stony Brook has already been mentioned.

The two materials used from the beginning for the construction of low β-cavities are still in use. Lead resonators obtained by electrodepositing a few μm of Pb on a copper substrate have the merit of easy and cheap fabrication for complicated geometries and profit from the high thermal conductivity of copper. Nb has greater potential with respect to critical fields and RF resistance but its technology is more difficult to master and more expensive. The technology of sputtering thin Nb-layers on Cu[20] which is already applied to cavities for electron acceleration may be an interesting alternative if sputtering or another method of deposition can be mastered for the complicated geometries of low β structures. Comparable complexities are incidently found in the coupler regions of electron accelerating structures so that these structures also could benefit from progress in deposition techniques. Similar arguments apply of course to Nb_3Sn, NbSn or lead-tin deposits.

Amongst the low β-structures developed during the last 3-years we mention the three shown in fig. 1.

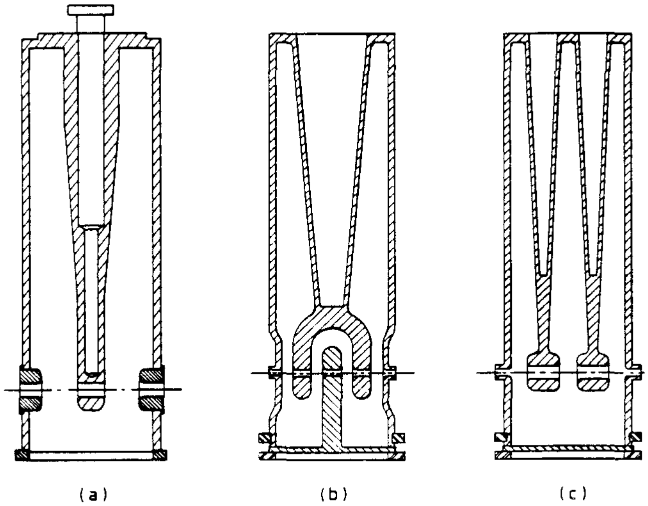
(a) (b) (c)

Fig. 1 Three different types of low β structures: (a) quarter wave; (b) 4-gap interdigital; (c) half-wave (not to scale).

- The coaxial quarter wave resonator[21] has no separable joint in high current areas and profits from a broad transit time factor making it particularly adequate for light ion acceleration.
- The 4 gap (interdigital) resonator[22] has a forked drift tube with 4 accelerating gaps and is especially suited for low β-acceleration ($\beta \gtrsim 0.007$).
- The half-wave resonator[23] is a two-gap structure which allows high accelerating voltages and is suited for an intermediate β-range.

All three structures are based on quarter wave resonant lines with straight inductors which gives them a great mechanical stability at the expense of a larger transverse dimension.

Experimental results[24] on these new types of structures have been obtained in the frequency range of 50-350 MHz and in a β-range of 0.008-0.2. Fields of at least 3-4 MV/m can be reached routinely and Q_0 values of a few 10^8, nearly independent of field levels are at hand. Multipactor can still be an annoyance but is no longer a major problem if clean conditions for surface treatments and assembly are applied. Processing at very high RF power levels[25] has sometimes produced large increases in accelerating fields. The most serious field limit tends to be electron loading from field emission sources. The mechanical stability is much less of a problem than for the older helix and split-ring structures.

The possibilities of these cavity designs can be illustrated by the new s.c. heavy ion injector planned at Argonne[26]. The present Argonne facility uses a tandem accelerator injecting in a s.c. linear accelerator. This injector scheme limits beam currents severely and is unable to accelerate ions in the upper half of the periodic table. It is intended to replace the tandem by a very low velocity (3 MeV) linac which can be operated with an open air HT-platform of 350 kV. One foresees to use 4-gap resonators with three staged geometries covering a β-range of 0.007-0.03 and 3-gap half-wave resonators for a β-range of 0.03-0.07. This combination will allow much higher beam currents and an acceleration of ions up to mass 80. In a second phase more resonators throughout the velocity range will be added and it is hoped that the refined velocity staging will enable acceleration of ions of lower specific charge and of higher masses like e.g. uranium ions. First tests with a 48.5 MHz interdigital Nb-structure for $\beta < 0.01$ show very promising results and accelerating fields up to 10 MV/m have been reached with a typical $E_{acc} = 8$ MV/m ($U_{acc} = 800$ keV) at 8 W input power[26].

Superconducting structures for electron acceleration

For a long time a considerable effort has been devoted to the understanding of surface defects limiting the accelerating fields. Careful surface treatments and improved inspection methods allowed to avoid larger defects or to eliminate them after their localisation. In this way, fields could be gradually increased but one could anticipate that at much higher field levels the size of defects to be detected and to be eliminated would become very small and their number prohibitively large. It was pointed out by H. Padamsee[27] that the threshold field for thermal instabilities could be increased if the thermal conductivity of the cavity wall is improved. Fortunately the heat conductivity of the Nb initially used for cavity fabrication lent itself to substantial improvements, essentially by reducing the interstitially dissolved elements O, N, C and H. A close collaboration with industry allowed to raise RRR values for Nb material from a typical 40 (corresponding to a heat conductivity $\lambda = 10$ W/m x K at 4.2 K) to values between 150 and 200. These values could even be substantially improved by the method of yttrification at ~ 1250°C developed at Cornell University[28]. Starting from high purity Nb with RRR ~ 120 now commercially available, RRR values could be pushed up to 600. A similar process using much cheaper titanium foils[29] but requiring a slightly higher temperature has also been tried successfully and has allowed to reach RRR values up to 500.

Model calculation for defect stabilisation have shown that breakdown fields scale aproximately with $\sqrt{\lambda}$ for a given type of defect. This behaviour has been confirmed by many cavity tests at different frequencies. In fig. 2 a compilation of some latest results is shown.

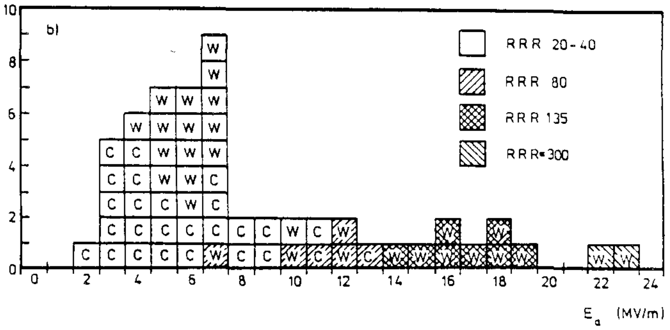

Fig. 2 Histogram of test results for single cell, 3 GHz Nb-cavities of different RRR (C: CERN, W: Wuppertal).

The combination of defect elimination and high thermal conductivity Nb-material has allowed in the last years to reach in a much more reliable way fields of 5-15 MV/m in multicell cavities[5,6]. As examples we quote the results obtained with CEBAF prototype cavities (5-cell cavities with waveguide couplers of the Cornell design[13]) fabricated by industry which reached accelerating fields of 6-8 MV/m at the first cooldown[30]. At KEK a single cell 500 MHz cavity with RRR = 80 has reached similarly a field of 7.6 MV/m[31]. The first LEP prototype 350 MHz, 4-cell cavity fabricated at CERN[32] has reached without guided repair of defects an accelerating field of 7.5 MV/m with a Q_0-value of 3 x 10^9 at the design field of 5 MV/m. A 20-cell 3 GHz cavity for the Darmstadt/Wuppertal recyclotron has reached 7.8 MV/m.

Much higher fields have already been obtained in single cell cavities like e.g. in a 1.5 GHz cavity at Cornell[34] which reached 22.5 MV/m and in a 3 GHz-cavity at Wuppertal where 23.1 MV/m[33] were reached after an yttrification of RRR = 80 Nb material (fig. 3). However these excellent results should not hide the fact that today the accelerating fields reached in s.c. cavities decrease considerable with increasing cavity length as can be seen from fig. 4. This figure also shows that the maximum voltages $E_{acc} \times \ell$ do not depend in a significant way on frequency.

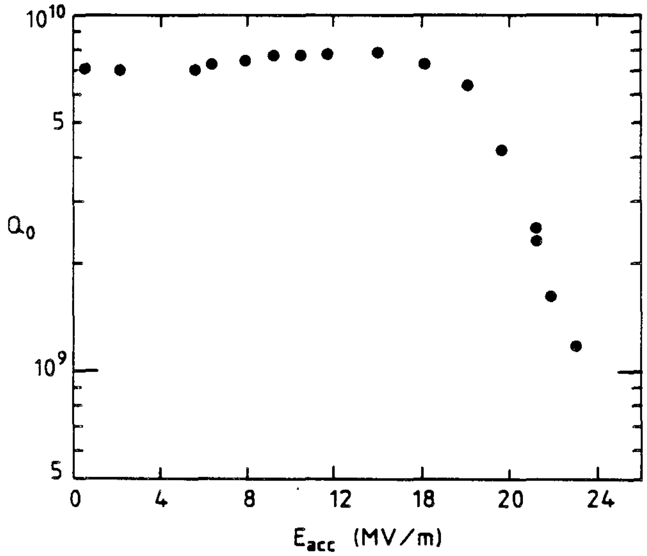

Fig. 3 Q-factor as a function of accelerating field of a 3 GHz, single cell Nb-cavity after yttrification (RRR = 300). (Courtesy Univ. of Wuppertal).

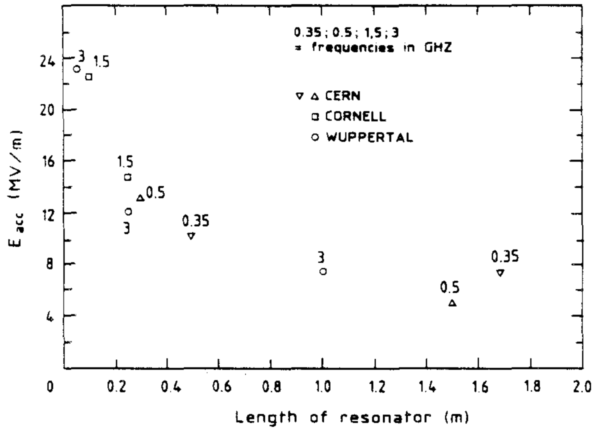

Fig. 4 Maximum acceleration field reached in Nb-cavities as a function of total cavity length.

Nb coated Cu cavities

At CERN a different approach is pursued to increase the thermal stability of s.c. cavities against defects. The niobium is replaced by OFHC copper and a Nb layer of 1-5 µm thickness is deposited by sputtering on the copper[35]. This method not only makes good use of the large thermal conductivity of OFHC copper (λ = 460 W/m x K) but gives also a possibility for producing Nb-layers largely free from foreign material clusters. In addition low RRR can be expected which corresponds to higher Q_0-values[36].

Two methods of sputtering Nb on Cu-surfaces have been applied. Bias diode sputtering[20] at a voltage of 1400 V and at an argon pressure of 5 x 10^{-2} torr has been first tried but has the drawback of a complicated niobium cathode and rather low sputtering rates (5 µm/24 h, depending on geometry). These drawbacks can be overcome by magnetron sputtering[37] at a voltage of 700 V in a magnetic field of about 100 G and at an argon pressure of 2 x 10^{-4} torr. A simple cylindrical Nb cathode can be used and the sputter rate is increased to about 1 µm/h. Both methods have given results with 500 MHz monocell cavities which are comparable with performances of solid Nb cavities[38] (fig. 5). At present the sputtering of a 4-cell, 350 MHz LEP cavity is prepared.

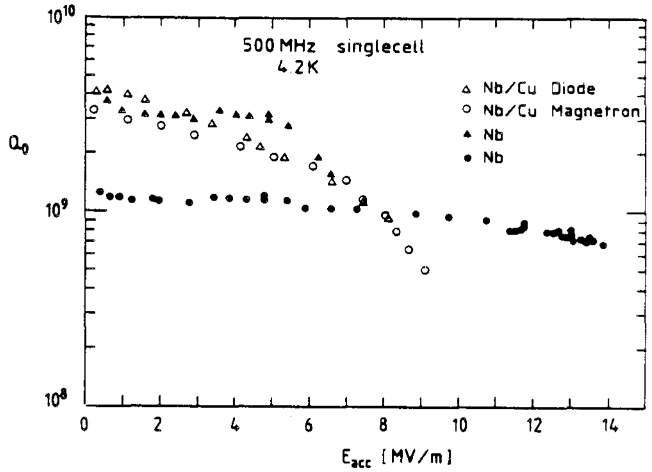

Fig. 5 Comparison of Q-values obtained in 500 MHz single cell cavities made from Nb and from Cu sputtered with a layer of Nb. For the Nb/Cu magnetron measurement no magnetic shielding was applied. For the lower Nb curve, the Q is limited by losses at the beam tube covers.

A few conclusions can already be drawn from the cavity measurements performed up to now[38]. Both methods give typical accelerating fields of 8 MV/m and a maximum of 10.8 MeV/m has been reached. Residual resistances down to 4 nOhm have been obtained and are generally somewhat lower than for solid Nb-cavities (table 1). No thermal breakdown has been observed up to the highest fields reached, except for one case where a protruding spike acted as a strong electron source. Q-values always show a decrease with increasing field levels which is generally stronger than the ones observed with solid Nb cavities (fig. 5). There are hints that the Q-decrease is correlated with the surface roughness of the underlying Cu. The adhesion of the Nb-layer to the Cu-substrate is still a problem. Q-"switches" at definite field levels and their hysterisis behaviour points towards regions with poor thermal contact. T-mapping and direct inspection have allowed to establish a clear correlation between Q-switches and blisters whose diameter may range from 0.2 mm to many mm. An investigation of the Nb layers peeled off from the blister regions has shown that contaminations like dust, surface impurities or rinsing residues are nearly always present below the blisters.

A very interesting result concerns the behaviour in an external magnetic field. It is well known that external fields increase the residual resistance of s.c. cavities. This behaviour, as measured in a Nb 500 MHz cavity is shown in fig. 6. Nb layers in Cu cavities of similar geometry show nearly no dependence of R_{res} on the external magnetic field.

TABLE 1 - Niobium material parameters[38]

	Solid Nb		Diode sputtered	Magnetron sputtered
RRR	100	35	9-14	3-9
$\Delta(k_B T_c)$	1.98	1.98	1.98	1.98
R_{res} (nOhm)	11-76	17	13-15	4
R^{BCS} (4.2 K)(nOhm)	81-100	73	59-61	59

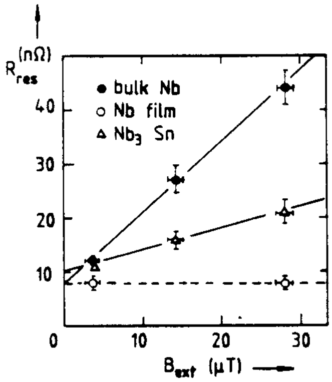

Fig. 6 Dependence of residual resistance of 500 MHz single cell cavities on an external magnetic field for Nb, for Cu sputtered with Nb and for Nb_3Sn.

Some material parameters of niobium coatings have been studied and a comparison with parameters of Nb cavities is given in table 1. The most obvious difference is to be found in the RRR value which does itself reflect in the values of the BCS resistance. There are also first indications[39] that magnetron sputtered layers (which are smoother than diode sputtered layers) show a decreased field emission as compared to solid Nb surfaces treated by standard chemical polishing and rinsed with ultrapure water. All these effects are now under study and it is hoped that a better insight in some properties of superconductors will be gained from these investigations.

Initially the Nb-Cu programme was started at CERN because it was expected that the copper would increase the thermal stability against defects to a point where thermal breakdowns could be avoided in the accelerating field range interesting for LEP. This has been confirmed and it is of obvious importance for any large s.c. accelerator. Another argument in favour of the Nb/Cu technology is a reduction of cavity costs. This reduction is particularly large for low frequency cavities like the ones foreseen for LEP (f = 350 MHz). It has been estimated that Nb material costs for these cavities represent 25% of the total cost (cavity, cryostat, couplers, tuners and vacuum systems) if commercially available niobium of high RRR is used(*).

Nb_3Sn cavities

Among the A15 materials which are characterised by high critical temperatures and by high critical fields, Nb_3Sn has gained a particular attention for s.c. cavities. Recent results of Nb_3Sn cavities have been summarized in refs 40 and 41.

At Wuppertal University[41], 3 GHz single cell and five cell cavities submitted to the well known vapour diffusion process (2 x 20 h at ~ 1170°C, Nb_3Sn thickness of ~ 3 µm) have given accelerating fields up to 7.2 MV/m. The lowest residual resistances reached at 4.2 K (with R_{res} = 27 nOhm) and correspond to a reduction of a factor 55 with respect to Nb at 4.2 K, the theoretical factor being 150. At CERN[42], a 500 MHz single cell cavity has been treated at 1025-1050°C for a period of 2 x 8 h. The low temperature has limited the Nb_3Sn thickness to about 0.9 µm, nevertheless $Q_0 = 2.4 \times 10^{10}$ at 4.2 K, corresponding to R_{res} = 11 nOhm has been reached. This is a decrease of a factor 7 with respect to Nb at 4.2 K. The result confirms that R_{res} of Nb_3Sn decrease with decreasing frequency.

Q-curves are still characterized by a strong decrease towards higher fields and by "Q-switches" which seem to be caused by weak spots with critical temperatures well above 4.2 K and which occur already at very low fields. Residual resistances depend on the cooldown rate[41]. A dependence on external magnetic fields similar to the one observed in Nb cavities (fig. 6) is also found.

More work on Nb_3Sn and other A15 superconductors would be very desirable. If their potential can be more fully exploited, operation at 4.2 K of linear accelerators in the GHz range becomes envisageable. Moreover, the high critical fields combined with very low r.f. losses make them particularly interesting for linear collider applications.

Cryostats and tuners

It is understandable that for many years the development efforts in RF superconductivity were mainly concentrated on cavity performances. As performances adequate for the next generation of s.c. accelerators can now be reached with much higher reliability more attention should be paid to the design of simple and economic cavities, cryostats and couplers.

A cost estimation of s.c. cavity systems for a frequency range of 1-1.5 GHz gives the following cost distribution:

- Cavity:	~ 35%.
- Cryostat:	~ 30%.
- Couplers:	~ 20%.
- Tuners, vacuum system:	~ 15%.

At least 65% of total costs will have to be spent for the equipment surrounding the s.c. cavities. Cryostat layouts and construction in particular have not yet received enough attention and there is in our opinion still room for simplifications in their design and construction.

Cryostats for large accelerator systems should be made modular and should allow a high accessibility to all critical parts of the cavity like couplers, tuners, and beam tube connections so that installation, repair or removal from a beam line are as simple as possible. Assembly of cavities and connections with the beam vacuum system should be possible under clean and dustfree conditions. A lateral (and not axial) removal of cavities and cryostats from a string of units installed in an accelerator tunnel would be desirable.

Recently a cryostat conceived along these lines of thinking for the LEP 350 MHz, 4-cell cavities has been constructed and tested at CERN[43] (fig. 7). The He-vessel is made of thin stainless steel sheet and welded around the cavity. It has a corrugated shape which reduces the liquid helium volume to 200 ℓ and which can be easily

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(*) For similar cavities at 1500 MHz with coaxial couplers this percentage would be only ~ 5%.

matched to the requirements of the coupling port geometry. The main coupler and higher order mode couplers which are of a coaxial type are mounted on Conflat type flanges welded to the He-vessel. The longitudinal rigidity of the He-vessel is kept smaller than the one of the cavity so that frequency tuning by a change of total cavity length is not inhibited. The cold shield is made of large removable Cu-sheets thermally linked to a copper tube frame by means of mechanical clamping devices. It is cooled by He-gas deviated from the main stream of evaporated He-gas. The vacuum vessel consists of a simple supporting frame with reinforcing staves wrapped in a thin stainless steel sealing envelope. Vacuum tightness is obtained by rubber gaskets. The sealing skin, staves and cold shield can be removed laterally and provide full accessibility to the cavity and to all critical parts like coupler and beam tube connections. The modular design allows to join as many units as needed and the large accessibility makes assembly under clean, dustfree conditions possible. Frequency tuning[44] is achieved by changing the length of three tubular rods anchored to the cavity end flanges and located inside the insulation vacuum. The middle part (~ 1 m) of these rods is made from pure nickel and its length can be changed in two ways.

The magnetic field of a coil surrounding the nickel tube produces a magnetostrictive effect allowing fast changes of small amplitude (~ 20 µm). A slow change of large amplitude (~ 2 mm) is obtained by thermal dilatation produced by a cold He-gas flow whose temperature can be adjusted and stabilised by a simple, electrically driven heat exchanger. This type of frequency tuner therefore has no moving parts.

The first test of the cryostat with a 4-cell LEP cavity and its tuner system has shown no major problems. The static overall losses (without main coupler) are 14 W. A large part of these losses is due to the beam tube connections between 4.2 and 300 K at both ends of the cavity. It will be greatly reduced once 8 cavities are housed inside a common vacuum tank as it is foreseen for LEP.

Couplers

The design of couplers for s.c. cavities has to match requirements of RF, cryogenics and of mechanical layout - sometimes contradictory - and a great deal of mastery has already gone into their development and testing[45,46].

For higher order mode (hom) couplers, waveguide structures with their low frequency cut-off offer an obvious approach because the fundamental mode can be easily suppressed and no stringent mechnical tolerances are needed. This advantage is however balanced by the non-circular cross section of waveguides, RF joints and RF loads which tends to increase the complexity of the cryostat.

At frequencies below ~ 1 GHz the size of waveguides makes their use impractical. Therefore one has pushed the development of coaxial couplers located at the beam tubes of cavities[47]. These couplers allow a simpler cryostat design and RF joints can be based on the well-known and reliable Conflat type joints. Also completely welded versions are under consideration. They can be easily matched via a (broadband) coaxial line to an RF load located outside the cryostat. This is an obvious advantage for linear accelerators where the hom power to be handled does not exceed the kW range and where type N connectors can be used. These couplers have to be combined with a rejection filter for the fundamental mode which asks for a relatively complex structure and for tight mechanical tolerances. At present developments are pushing for a simplification of these layouts. It is expected that the new designs can be scaled to a frequency range well above 1 GHz. A limit will be set towards higher frequencies by the smallness and mechanical tolerances of the coupler-filter part.

Recently new compact hom couplers types (fig. 8) have been developed with Q_{ext} for the most dangerous hom which approach the ones realized already with waveguide couplers (Table 2) and which will be adequate for the requirements of high current storage rings and of recirculating linacs.

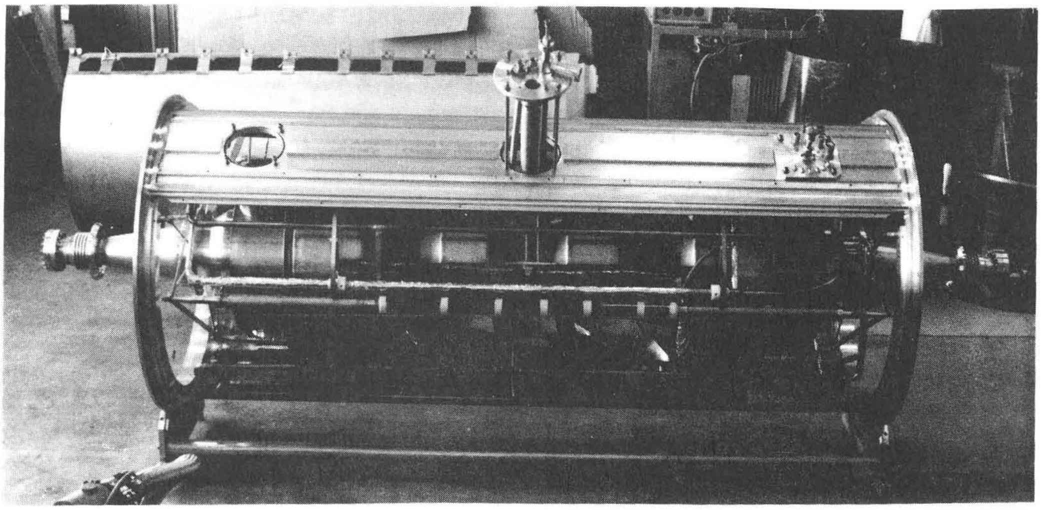

Fig. 7 Photography of the cryostat for a 350 MHz 4-cell cavity for LEP. The openings for the main coupler and for the He-feedlines can be seen. Behind the sealing envelope of the vacuum vessel.

TABLE 2 - Typical Q_{ext} obtained for a few important higher order modes

	f (MHz)	N_{cells}	Layout of hom couplers at beam tube	Q_{ext} (10^4)		
				TM_{011}	TE_{111}	TM_{110}
Cornell/CEBAF[50]	1500	5	2 waveguides at 90°	0.07-0.16	0.4-3.2	1-1.3
LEP[51]	500	4	2 coaxial electric	1-2.3	0.7-1.7	1-2.3
	350	4	2 coaxial electric	2.5	1	0.6
HERA	500	4	3 two-stub[48], magn. and elec.	0.06	0.4-5	0.2-4

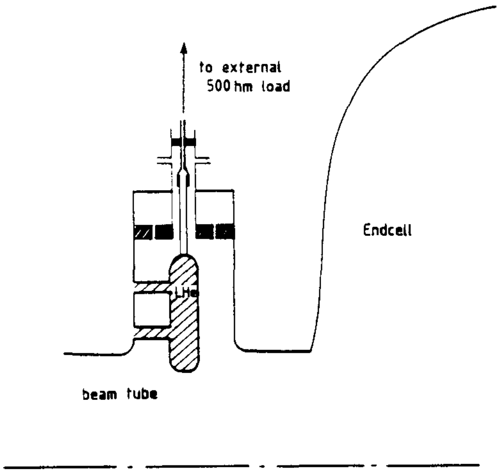

Fig. 8 Schematic layout of a compact two-stub coupler[48] (table 2).

Fundamental couplers of coaxial designs which can handle more than 50 kW RF power have already been developed and tested[47,49]. For linear accelerators with beam currents in the range of 100-200 µA and gradients of about 5-10 MV/m the RF powers to be handled range in the kW region and coaxial designs should be adequate up to frequencies of at least 3 GHz. At even higher frequencies waveguide couplers would again be the obvious solution.

Conclusion

The technology of RF superconductivity has found during the last years an ever increasing interest for accelerators. The progress in cavity materials, surface treatments and clean room assemblies has allowed to raise gradually accelerating fields to a level adequate for large heavy ion and electron accelerators. New types of cavities for heavy ion acceleration have been developed with increased mechanical stability and which reach fields of 3-4 MV/m and Q-values of a few 10^8. For electron acceleration, multicell cavities with fields of 5-10 MV and with Q_0-values of a few 10^9 are available. Fabrication of cavities by industry has started.

The performances of Cu cavities sputtered with a thin layer of Nb approach the ones of solid Nb and it is hoped that these cavities will allow a better thermal stabilisation of defects and a cheaper fabrication of low frequency cavities. Thin Nb layers show some interesting properties like e.g. less sensitivity to external magnetic fields. Their study will hopefully give an improved insight in s.c. properties and fructify the technology of high T_C superconductors like Nb_3Sn and NbN. Besides cavities simpler and cheaper layouts for cryostats, couplers and tuners are under development and promising progress has already been made. This is essential if one wants to fabricate these acceleration systems for the planned large storage rings and linear accelerators at realistic costs.

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