RF SUPERCONDUCTIVITY, A STATUS REVIEW

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I Abstract

The subject of this paper is a review of superconducting cavities for accelerator application with special emphasis to β = 1 structures. The layout of a typical accelerating unit is described and important parameters are discussed. Recent cavity measurements and storage ring beam tests are reported and the present state of the art is summarized.

II Introduction

About twenty years ago developement work started to use superconducting cavities for accelerator application. Superconducting cavities promise to reach high field gradients. In the case of Niobium values around E(acc) = 50 MV/m (for β = 1 structures) can be expected as a thermodynamical limit. Superconducting cavities can be operated under continuous wave conditions so that they are superiour to conventional normalconducting cavities wherever cw operation is needed. In the first years lead was used as superconducting material. At low frequencies (f < 200 MHz) the enhanced loss of Pb as compared to Nb is tolarable so that electroplated lead-copper cavities still offer an alternative solution in this frequency range. In most applications, however, Niobium is used as favourite material. Niobium compounds, for example Nb(3)Sn promise even superior values in respect to low losses and high field gradients but they still show only moderate field gradients.

Early β = 1 cavities were plagued by multipacting phenomena and quenches at welds or material defects. Meanwhile one point multipacting is eliminated by spherical or eliptical cavity design. Improved techniques of fabrication were developed (rhombic raster welding, chemical or electrochemical cleaning, dust free rinsing) and the Niobium material itself could be fabricated in better quality and with a (nearly) damage free surface finish. Reducing the impurity content of O, N, C either during the sheet production or after the cavity fabrication by heating together with getter material greatly improved the thermal conductivity of the Niobium (typically from λ = 10 W/m/K to λ = 100 W/m/K). A higher thermal conductivity allows more heating (i.e. higher fields) at a defect until a thermal runaway triggers a quench. Today Niobium cavities (β = 1) are usually limited by field emission. Quench limitations below E(acc) = 5 MV/m still occur but they are exceptional due to material, fabrication or handling errors.

For β < 1 application helix resonators (HER) were used at first but they suffered from high sensitivity to mechanical vibrations. This problem was attack by a modified mechanical layout and by the different design of a split loop resonator (SLR). Recently quarter wave resonators (QWR) have been developed. They have a good mechanical stability and a relatively broad velocity acceptance. The low operating frequency around 100 MHz allows to use Cu-Pb instead of Nb as superconducting material. The enhanced loss of Pb is counterargued (amongst others) by lower fabrication cost so that the material decision is governed by available fabrication techniques or existing laboratory infrastructure. On-line gradients of E(acc) around 3 MV/m have been demonstrated for Nb as well as for Cu-Pb resonators. It seems as if considerable higher values of E(acc) are attainable more easily with Nb resonators although improvements in Pb-plating techniques might change this situation.

Work with superconducting cavities is done at many places in the framework of planned, approved or operating accelerator projects. A recent compendium of all this work can be found in the proceedings of the third workshop of superconducting cavities [1]. Fundamentals of superconducting cavities are explained and literature references can be found in [2].

III Low β Structures

Three different types of low β structures are scetched in Fig. 1. They have been developed at different laboratories and they are in use in operating heavy ion linacs. In tabel 1 the operating linacs are listed. Operating experience

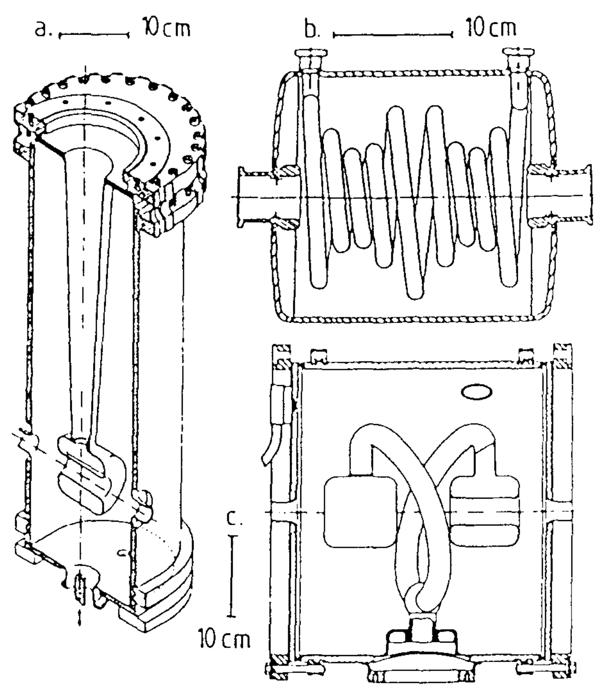

Fig. 1: Typical low β accelerating structures f_0 ≈ 100 MHz (a, quarter wave resonator QWR; b, helix resonator HER with improved mechanical stability; c, split loop resonator SLR)

Laboratory	#	resonator type	resonator f₀ [MHz]	material	operating since
Argonne	45	SLR	97/146	Nb	1985
CEN	48	HER	81/135	Nb	1987
Florida St. Univ.	12	SLR	146	Nb	1987
St. Brook	40	SLR	150	Cu/Pb	1983
Wash. Un.	36	QWR	150	Cu/Pb	1987

Tab 1: Operating linacs with low ß structures (SLR: split loop resonator, HER: helix resonator. QWR: quarter wave resonator)

exceeding 40 000 hours have been collected at Argonne and Stony Brook and no basic failures have been reported. The on-line gradients around 3 MV/m might deteriorate after prolonged operation without maintenance but can be recovered by standard high field conditioning. At Argonne the quarter wave resonator has been modified for special use in very low ß region ("interdigital line"). Detailed information is given in another contribution to this conference [3].

IV The Superconducting RF-Module (ß = 1)

Standing wave structures (ß = 1) are developed for linear or storage ring application at different places: CEBAF, CERN, CORNELL, Darmstadt/Wuppertal, DESY, HEPL, KEK and SACLAY. The cavity itself is one important part of the complex accelerating system. The other subsystems like cryostat, cryogenics, coupler and tuner have to be developed, too, for an operating module. In the following the complete module with all subsystems will be discussed. Fig. 2 shows the cross section of a typical module layout. Here two cavities are housed in one cryostat. Each cavity has its own high power input coupler and several higher order mode couplers are located at the beam pipe. Tuning is done by lengthening the whole cavity. Cavity and coupler are cooled in a bath of LHe.

1 Cavity Design

Rounded design is generally adopted to avoid one point multipacting. A weak barrier of two side multipacting at the equator still occurs but can be processed easily [4]. In contrast to normal-conducting cavities superconducting resonators are not optimized for shunt impedance values. Here design criteria are: small values of surface field enhancement (E(peak)/E(acc) and H(peak)/E(acc)), field flatness of higher modes to allow beam pipe couplers and to avoid trapped modes. Frequencies from 350 MHz to 8 GHz have been used. High accelerating gradients (E(acc) > 15 MV(m) could be demonstrated in small (i.e. high frequency) cavities. High voltage gain U(acc), however, is needed for linac or storage ring application which have been measured at lower frequencies. The choice of frequency is governed by arguments like low transverse impedances, non subatmospheric LHe system, low number of cells and high stored energy per metre (low frequencies) or easy handling because of small size, reduced material costs, small LHe volume (high frequencies) or by given requirements of the specific application. The number of cells per structure should be as high as possible in order to get a high filling factor. In contrast the number of cells should be small to get a strong damping of higher order modes by beam pipe couplers. Intensive higher order mode measurements and calculations show [5] that for a typical storage ring application the number of cells should not be higher than five. In the case of high beam current the maximum allowable window power sets another limit to the length of the structures and thus to the number of cells.

The diameter of the beam pipe is chosen to be as large as possible to propagate the higher frequencies to the location of the higher order mode couplers. A cut off frequency of the beam pipe below the higher order mode frequency of interest is not in all cases a sufficient condition for an energy propagation. In addition sufficient coupling between cavity and beam pipe fields is needed. As shown by measurements and calculations [6] there exist a few modes (above cut off), which show no coupling to the beam pipe. They only can be damped by couplers in the cells, so that the original idea of a single mode cavity [7] cannot be realized.

2 Higher Order Mode Coupler Design

Higher order mode couplers at the cavity cell have been abandoned because of the danger of multipacting. At the beam pipe different couplers have been successfully developed: coaxial type of couplers with one or two step fundamental filters [8, 9, 10] or waveguide couplers with natural fundamental cut off damping [11]. The couplers might be flanged or be welded to the cavity. The higher order modes of a superconducting cavity can be damped to quality factors equal or even smaller to those of a normal conducting copper cavity.

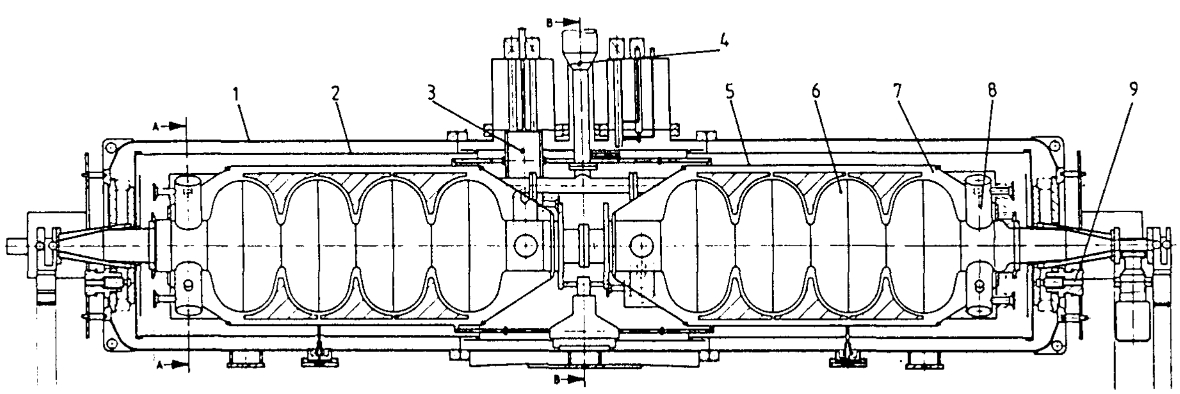

Fig. 2: Cross section of the HERA superconducting RF module as an example for the complex layout (1: vacuum vessel, 2: radiation shield, 3: LHe-distribution, 4: safety line, 5: LHe- vessel, 6: Nb-cavity, 7: LHe, 8: HOM- coupler, 9: tuning device)

3 Input Coupler Design

With increased beam current the input window becomes a crucial part of the superconducting RF module. For example at the HERA beam current of 60 mA a 500 MHz 4-cell cavity at 4 MV/m transfers 200 KW RF power. Under those conditions a restriction of the window power limits the achievable accelerating gradient. A break of the input window is considered to be the most likely and at the same time also the most dangerous accident because of immediate LHe boil off. For high power coaxial input lines windows of disc- [12] or cylinder [13] design are used. Also double windows have been built [14]. Sensitive diagnostics interlock the klystron power. So far no severe window accident has been reported but it is clear that for a large scale application of superconducting cavities the failure rate of windows experienced with normal conducting cavities cannot be accepted.

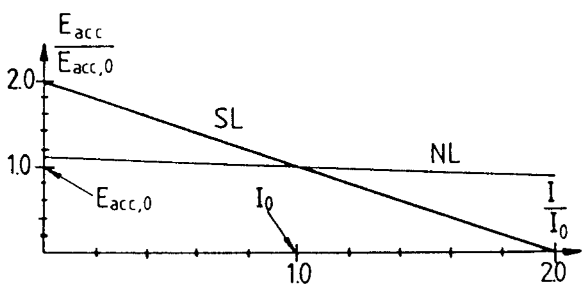

Fig. 3: Variation of accelerating voltage by changing beam current. The cavity is matched to the generator (no RF reflection) for a beam current I_0 at E(acc),0. Fixed coupling and fixed forward RF power is assumed (SL: superconducting cavity, NL: normalconducting cavity)

In a superconducting cavity the coupling between generator and cavity strongly varies with beam current loading. Only nearby matched condition all the offered generator power is transferred to the beam. Furthermore the achievable accelerating gradient decreases to zero for a beam current twice the matched value (see fig. 3) [15]. Therefore a variable high power coupler is needed to operate a superconducting cavity in an economic way.

4 Tuning of a superconducting Cavity

Because of the danger of multipacting tuning pistons in a cavity cell are not used.The resonance of the cavity is controlled by shortening or lengthening the whole length like an accordion. This is done by a variety of driving systems: motors and gear boxes at cryogenic or at room temperature, piezo-electric or magnetostrictive or thermal expansion or hydraulic drivers. The tuner has to fullfill different requirements: to adjust the correct frequency after cooldown, to follow any frequency swing during operation, to detune in case of a bad cavity and to compensate for any unwanted frequency vibration. According to different operating conditions only slow or also fast tuners are needed. Frequency (and phase) jitter due to mechanical vibration cannot be eliminated by a mechanical tuner but needs a complex RF phase and amplitude control [16].

5 Cryostat

Horizontal LHe-bath cryostats are used for accelerator application. Different techniques are applied to close the inner LHe-vessel: Indium joints, brased or welded connections. The standby losses range from 3 W/m to 6 W/m. These numbers are high as compared to typically 0.5 W/m for superconducting magnets.

Considerable safety problems exist at DESY and KEK applying the rules of the high pressure vessel index. The lack of mechanical data of Niobium at cryogenic temperatures is not only a problem of "legal safety". These data are a need for cryostat engineering under safety aspects ("real safety") and more attention has to be paid to this field. Following safety arguments the large volume of LHe of several hundred liters per metre can be reduced by shaping the helium vessel or by using displacement bodies.

Superconducting magnets can withstand pressure up to 15 bar because of their tubular construction. Superconducting cavities might collapse above 3 bar. This results in big vent-lines and low pressure safety valves. One way out of these problems is the consequent application of pipe cooling to superconducting cavities. This cooling technique also simplifies the LHe distribution system and decouples the cavity from pressure variations in the LHe room.

At CERN an easy dismountable vacuum shell has been developed [17]. This construction allows to have access and to exchange one out of several cavities which share a common vacuum system.

6 Costs of a superconducting RF-module

The price of a superconducting RF-module might vary with design and number of modules. The following data are based on the 500 MHz HERA design. Fig. 4 shows the relative cost distribution of the major components. The absolute costs are around 400 TDM per 1 m active structure. It should be pointed out that this number does not include costs for
- LHe production and distribution
- high power RF production and distribution
- interlock and controls
- assembly of the cavities in the cryostat
- cryogenic measurements
- repair cycles.

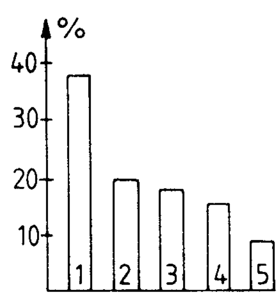

Fig. 4: Relative cost distribution (1: cryostat, 2: cavity, 3: coupler, tuners 4: Nb-material 5: pumps, valves..)

7 Materials for cavities

Niobium sheet material is used for most parts of a resonator. It can be delivered with high surface finish but a careful inspection (by eye, rust test, ultrasonic, oxydation) before and after the fabrication steps is still needed. Material with high thermal conductivity is preferred because it stabilizes quench centres. On the other hand the purification process needed lowers mechanical properties (yield strength) and also leads to higher RF losses. This is especially true for cavities which have been purified after fabrication by a heat treatment. Recently sheet material with high thermal conductivity and still high yield strength ≥ 100 N/mm² is available. Here the increase of the RF losses is less pronounced and is explained by a thin uppermost layer of reduced thermal conductivity.

Cu-cavities with a sputtered Nb surface have been intensively investigated [18]. Single cell cavities showed fields up to E(acc) = 15 MV/m at RF losses less than those of bulk Niobium. It is astonishing that sputtered Nb-Cu cavities are insensitive to frozen in magnetic flux. But still difficulties have to be overcome concerning reproducibility, especially for multicell structures with input and output coupler parts.

V Storage Ring Beam Tests

A summary of beam tests up to the middle of 1987 is given in [19]. Meanwhile several more tests have been carried out.

PETRA beam test

In November 1987 a prototype module for HERA has been tested in PETRA [20]. The two 500 MHz 4-cell cavities showed before and during the beam test values for E(acc) of 5.1 MV/m and 2.5 MV/m. The lower value was due to a quench at a bad weld which could not be repaired in time. The main purpose of the experiment was to test the higher order mode coupling scheme at single- and multibunch beam operation. The measured values agreed well with the expected data.

SPS beam test

In August 1987 and during spring 1988 a 4-cell cavity with 358 MHz resonance frequency (LEP-design) was operated in the SPS storage ring [21]. The cavity was equipped with HOM couplers according to the LEP conditions. In addition damping at the fundamental mode frequency was foreseen to lower the cavity impedance during the passage of the intense p-bunch of the SPS. The purpose of the test was

- to test a fully equipped LEP-cavity for a long period under operating conditions
- to accelerate electrons and positrons and to study the LEP injection
- to study the beam cavity interaction.

Up to now the cavity stayed cold in the SPS for 4000 h without degredation. Electrons were accelerated up to a maximum value of E(acc) = 7 MV/m.

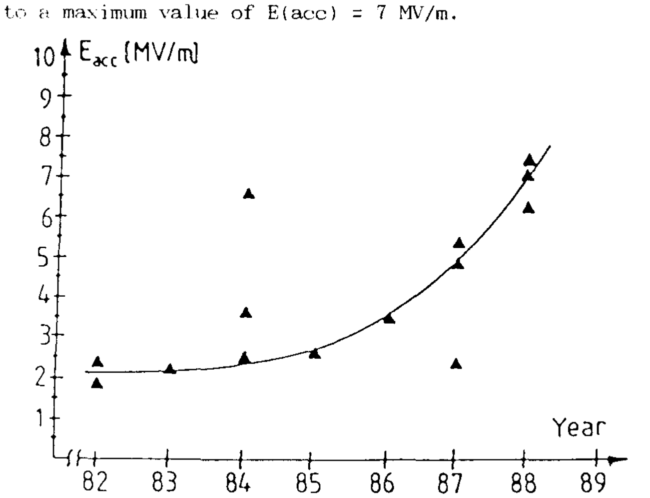

Fig.5: Accelerating gradient measured in beam tests at CERN (PETRA,SPS), CORNELL (CESR), DESY (PETRA), Karlsruhe (PETRA) and KEK (Tristan AR) [19]

TRISTAN beam test

Two 5-cell structures (508 MHz) in two individual horizontal cryostats have been tested in the accumulation ring of Tristan in October, November 1987 and in March 1988 [22]. Accelerating gradients of E(acc) = 6.3 MV/m and 7.5 MV/m could be reached. 86 kW of RF power was transferred to the beam through one input coupler and a maximum single bunch current of 69 mA was stored. Meanwhile 16 5-cell cavities have been tested (see next chapter) and will be installed in the main ring TRISTAN during the summer 1988.

VI Recent Cavity Measurements

KEK 5-cell cavities, 500 MHz

16 5-cell cavities have been tested in a horizontal cryostat prior to installation in TRISTAN [22]. The results in Fig. 6 demonstrate the high level of industrial fabrication. Meanwhile the 16 cavities have been installed in the tunnel and RF commissioning will start in November 1988.

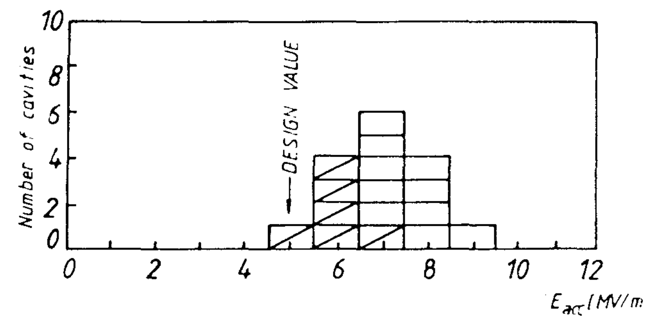

Fig. 6: Measured values of E(acc) of 5-cell 508 MHz cavities at KEK [22] (horizontal test prior to installation in TRISTAN
▭ still going up by RF processing
▨ almost upper limit)

CORNELL 1-cell cavities, 1.5 GHz

At CORNELL a series of single cell cavities has been tested to investigate the influence of chemical treatment versus heat treatment [23]. The result is given in fig. 7 and shows average values of E(peak) for chemical and heat treated cavities of 22 MV/m and 38 MV/m respectively after He processing. For comparison, the value of E(peak) has to be divided by a factor of 2.5 to get the equivalent number of E(acc) for this type of cavity [23].

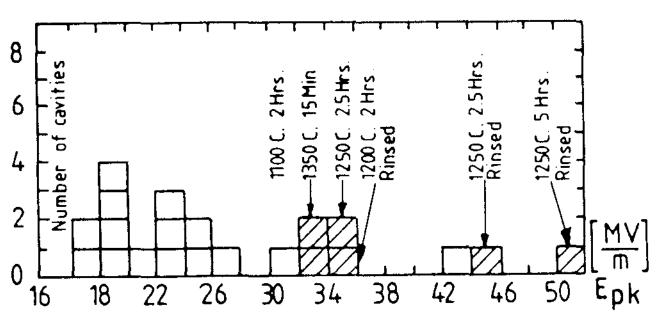

Fig. 7: Results of single cell measurements at CORNELL, 1.5 GHz [23]. Dashed areas represent heat treated cavities, open areas represent chemically treated cavities. The values shown have been reached after He-processing. All cavities were limited by field emission.

Pair Test Measurements at CEBAF

Four pairs of 2 x 5 cell cavities (1.5 GHz) have been tested in a vertical cryostat [24]. The measured values are given in fig. 8 and demonstrate that the specified value of 5 MV/m could be exceeded. Four cavities have been attached together in a horizontal cryostat. They have been measured at accelerating gradients of 6.7, 7.4 and 9.4 MV/m [24]. One cavity could not be excited to high fields due to a wrong coupling.

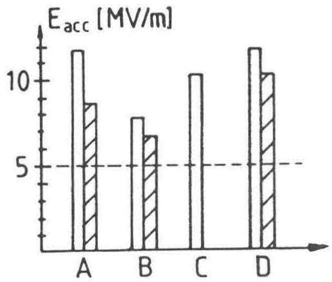

Fig. 8: Result of pair test measurements (2 x 5 cells) at CEBAF, 1.5 GHz (vertical test) [24]

DESY 1-cell cavity, 500 MHz, pipe cooled

At DESY a second cavity, fabricated by explosively bonded Nb-Cu and cooled by pipes has been measured (see Fig. 9) [25]. After He-processing E(acc) = 9 MV/m and a Q-value (low field) of 2.7 x 10^9 could be reached. An increasing degradation of Q_0 with increasing number of quenches has been observed (worst case down to Q_0 = 6 x 10^8). A warm up above T_c restored the original data. This phenomenon has also been observed with other composite materials (Nb-Pb [26], Nb_3Sn [27] and is believed to be caused by frozen in flux due to quench induced thermocurrents. Investigations are started to better understand and reduce this effect.

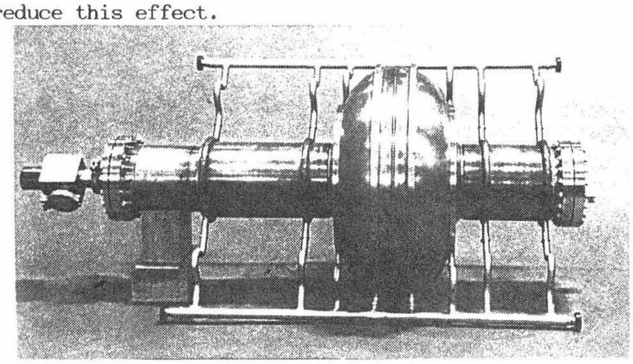

Fig. 9: 1-cell 500 MHz cavity. This cavity is fabricated by explosively bonded Nb and Cu and is cooled by pipes [25]

VII Field Emission

At surface electric fields above 20 MV/m field emission is the dominant limiting effect. The onset of field emission might start below E(peak) ≈ 10 MV/m depending on preparation or complexity of cavity surface. Experiments with dc-field emission of Nb-surfaces showed [28] that geometric protrusions are not the origin of field emission currents. The number and intensity of field emitters vary with heat treatment history [28]. Field emitters in cavities have been traced with temperature maps. In a recent experiment [23] condensed gases are made responsible for some field emission effects. So far field emission in cavities is not clearly understood and more investigation is needed to push cavities nearer to the thermodynamic possible limit.

VIII Conclusion

From the above information the following conclusions can be drawn:

- low ß structures operate in five heavy ion linacs without problems. Gradients around 3 MV/m are achieved with Nb and Cu-Pb resonators
- ß = 1 structures are developed for e^- linacs or storage rings. After prototype work the production or installation of acceleration units is on the way at different laboratories
- increased thermal conductivity of Nb and industrial fabrication techniques improved the performance of Nb cavities. The following accelerating gradients can be reached:
  E(acc) ≥ 20 MV/m, single cells, best values
  ≈ 10 MV/m, equipped structures
  ≈ 6-7 MV/m, result of beam tests
- best cavities are limited by field-emission. He-processing and/or heat treatment are adopted methods to increase this barrier. A radical remedy as well as a clear understanding of the field emission process are still open.

IX Acknowledgement

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X References

[1] Proceedings of the Third Workshop on RF Superconductivity, Argonne National Laboratory, ANL-PHY-88-1
[2] H. Piel, Fundamental Features of Superconducting Cavities for High Energy Accelerators, WUB 86-14
[3] L. M. Bollinger, Argonne, this conference
[4] W. Weingarten, Proc. of the Second Workshop on RF Superconductivity, CERN, Geneva (1984) 551
[5] B. Aune, ibid. ref. 1, p 163
[6] D. Proch, DESY, unpublished
[7] T. Weiland, DESY, 83-073, Sept. 1983
[8] E. Haebel and J. Sekutowicz, DESY, M-86-06
[9] G. Cavallari et al., ibid. ref. 1, p 565
[10] B. Aune, ibid. ref. 1, p 163
[11] J.C. Amato, ibid. ref. 1, p 589
[12] T. Takaaki et al., Proc. 13th Int. Conference on High Energy Accelerators, Novosibirsk, 1986
[13] B. Dwersteg et al., DESY, M-87-08
[14] W. Bauer et al., Nuclear Instruments and Methods in Physics Research, 1983, 214, (1983), 189
[15] W. Ebeling, DESY, M-87-13
[16] I. Ben-Zvi et al., Nuclear Instruments and Methods in Physics Research A 245 (1986) 1
[17] R. Stierlin, ibid., ref. 1, p 639
[18] C. Benvenuti et al., ibid. ref. 1, p 445
[19] D. Proch, ibid. ref. 1, p 29
[20] B. Dwersteg et al, Proceedings of EPAC-Conference, 1988, Rom
[21] W. Weingarten, CERN, ibid., ref. 20
[22] Y. Kojima, KEK, private communication
[23] Q. S. Shu et al., Cornell, CLNS 88/850
[24] R. Sundelin, CEBAF, private communication
[25] B. Dwersteg et al., ibid., ref. 20
[26] J. R. Delayen, ibid. ref. 1, p 469
[27] G. Müller, Univ. Wuppertal, private communication
[28] Ph. Niedermann et al., I. Appl. Phys. 59 892-901 (1986)