

WORK ON SUPERCONDUCTING SYSTEMS AT KARLSRUHE

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Introduction

At Karlsruhe, work is going on on two types of superconducting systems:

1. Superconducting magnets
2. Superconducting resonators

Since I am personally more familiar with the resonator work, the emphasis in this paper will be on this field. But since the effort going into magnet development for various purposes is considerable, I should like to refer the audience to recent review articles^{/1,2,3/} on the subject. I shall only mention two highlights, namely the successful installation of two superconducting quadrupoles in the hyperon beam at CERN and the construction of a superconducting solenoid for the CELLO experiment at PETRA.

Surface resistance and operating temperature

The advantages and limitation of superconducting resonators are well known by now. It is not difficult to reach in a reproducible way surface resistances low enough to guarantee a substantial saving in electrical power even taking into account the power taken up by the refrigerator. The surface resistance is the sum of two terms $R = R_{sc} + R_{res}$; R_{sc} is theoretically well understood and is a strong function of temperature T ($\propto \exp(-2 T_c/T)$, T_c critical temperature) and frequency ω ($\propto \omega^{1.8}$). R_{res} is less well understood, it depends on the amount of care taken in preparing the surface, but not strongly on temperature and frequency. R_{res} is of the order of 100 n Ω for surfaces in technically applicable resonators. This figure has to be compared with 8 m Ω for copper at 1 GHz and 300 K.

Since R_{sc} reaches the 100 n Ω level for niobium surfaces for a temperature of 3 K and a frequency of 1 GHz, we have two cases:

- 1) For frequencies well below 1 GHz, R_{res} dominates, so no extra gain is obtained by further reducing the frequency. Moreover the economically attractive operation at 4 K is acceptable.
- 2) For frequencies above 1 GHz, R_{sc} dominates, so frequencies should not be chosen

too high. Superfluid cooling at 1.8 K is preferable here, since the gain in resistance outweighs the extra cost of refrigeration per Watt.

Field limitations

Both magnetic and electric field limitations occur. Magnetic limitations occur at rf fields well below the known critical field for superconductors and are believed to be caused by local imperfections in the surface. This is confirmed by the fact that unusually low magnetic field limitations can often be eliminated by retreating the surface, thus eliminating a particularly bad spot.

Electric field limitations are related to field emission, which can become troublesome at peak fields of about 15 MV/m, and by multipacting phenomena which occur generally at lower fields. Obstinate multipacting have been observed mainly in the frequency range of 1 GHz and below, depending on details of the resonator geometry.

Karlsruhe activities

They are summarized in ref. ^{/4/}. Besides the basic research on superconducting surfaces (Nb ^{/5/} and Nb₃Sn ^{/6/}) and field limiting phenomena ^{/7/}, the main development activities in Karlsruhe are the following.

- 1) Proton Linear Accelerator Prototype
- 2) Heavy Ion Post-Accelerator Prototype
- 3) rf Separator
- 4) Application studies for e⁺e⁻ Storage Rings

I shall describe them in turn.

1) Proton Linac Prototype

This is our oldest project. Table I gives some parameters. Fig. 1 shows a helix resonator. I shall be brief on this project because although many components have been developed and tested ^{/4/}, the accelerator will not be fully assembled before the end of this year. So no overall performance can be reported yet. It may be interesting, though, to note some points.

- a) The 90 MHz multiple helix resonator shows superconducting properties ($R \lesssim 100 \text{ n}\Omega$, $E_p = 15 \text{ MV/m}$, magnetic limitation) which are reproducible even after months of storing. Multipacting occurs, but can be overcome easily.

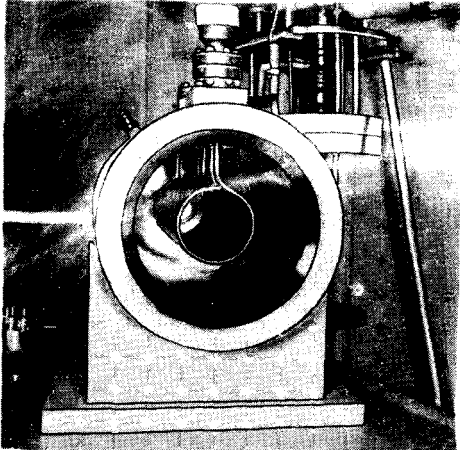


Fig. 1.

A resonator loaded with coupled helices belonging to the first part of the proton linear accelerator.

TABLE I

Parameters of the prototype proton accelerator

Energy range	0.75 - 6	6 - 7	MeV
Type of structure	coupled helices	Alvarez	
Frequency	90	720	MHz
Electrical length	5	0.5	m
Number of sections	9	1	
Energy gradient	1 - 2	2	MeV/m
Technical length		9	m
Beam current		≤ 0.4	mA
Operating temperature		1.8	K
Total He losses		< 100	W

b) The 720 MHz Alvarez section^{/8/} is limited by electrical fields. Operating at $E_p = 15$ MV/m is safe.

2) The Heavy Ion Post-Accelerator Prototype

This prototype^{/4,9-11/} consists of two single helical resonators, housed in a common cryostat. Parameters are given in table II. Single helix resonators (fig. 2) are chosen in this case in order to permit a selection of the appropriate velocity profile for various ions. The following features are noteworthy:



Fig. 2.

A single helix resonator for the heavy ion post-accelerator before assembly.

TABLE II

Parameters of the heavy ion post-accelerator prototype

Type of structure	single helix	
Number of resonators	2	
Operating frequency	108.48	MHz
Peak electric field	16	MV/m
Effective accelerating field related to helix length	2.3	MV/m
Energy gain/charge	0.57	MV
Technical length	1	m
rf cavity losses	2	W
Frequency modulation by vibration	500	Hz pp
rf power needed by fast tuner	100	W

- a) The device was operated for 500 h with the MPI tandem at Heidelberg at the design peak field of 16 MV/m.
- b) An enhancement of electron emission from the resonator surface was found only after accidental vacuum breakdown.
- c) Deliberate irradiation of the helices by Ni-ions did not affect the performance.
- d) 4.5 K forced cooling has been applied successfully and did not give rise to the anticipated vibrations due to bubble formation.
- e) A reactive fast tuner compensates the frequency jitter caused by the mechanical

vibrations of the helix. Starting and operating this system needs no human supervision.

Extrapolating from this prototype, an estimate of the economy of a superconducting post-accelerator yielding about 10 MV of voltage gain can be given; this is done in table III.

TABLE III

Extrapolated performance of a 10 MV voltage drop heavy ion post-accelerator

Technical length	17	m
Installed 4.2 K cooling power	150 - 200	W
rf power	2	kW
Total power consumption	200	kW
Total investments	2	M\$
Operating cost (excluding staff)	20 - 30	\$/h

3) The rf Separator

This separator^{/4,12/} is meant to separate kaons and antiprotons from pions up to 30 GeV/c at CERN. Fig. 3 shows one deflector. Parameters are given in table IV. The construction is completed (Fig. 4 and 5). Considerable difficulties have been encountered in achieving in the deflectors the same fields that were observed in every single one of the 5 sections making up the deflector. The following causes were considered:

- a) The rf joint between adjacent sections. But design fields could be achieved in pairs of sections joined together in the same way.
- b) Unflatness causing local fields enhancements. Since reliable field measurements by the Slater method cannot be performed at room temperature due to mode overlap, measurements were done at helium temperature. Unflatness could be reduced to 12% and can be ruled out as a case of limitation.
- c) The breakdown could be localized by observing with carbon resistors the heat pulse, or rather the bubble formed by it in operating above the λ -point of helium. It was found to be in the center cell of the structures right below the main coupling that includes a niobium bellows. Actually in one case a metal chip of above 1 mm^2 was found afterwards in that location. We have recently done away with the bellows and have cured this trouble, so we hope to be able to deliver the separator to CERN this year.

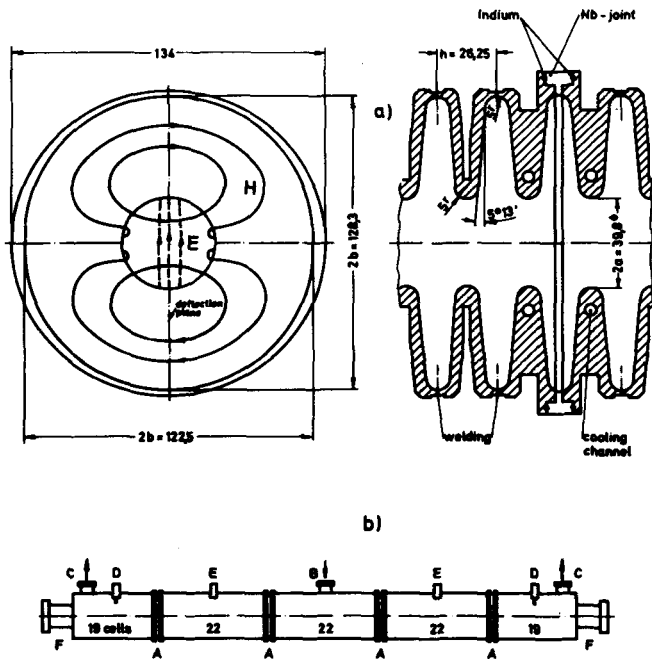


Fig. 3.

A deflector for the rf separator. Some fields are indicated.

- A = rf joint
- B = rf input
- C = rf probes
- D = fine tuner
- E = coarse tuner
- F = beam tuner

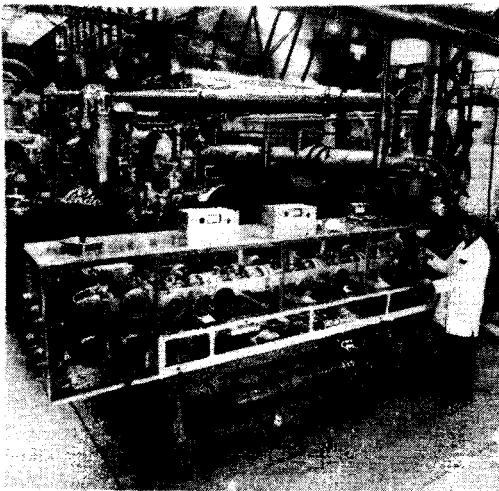


Fig. 4.

A deflector for the rf separator in the glove box where it is assembled.

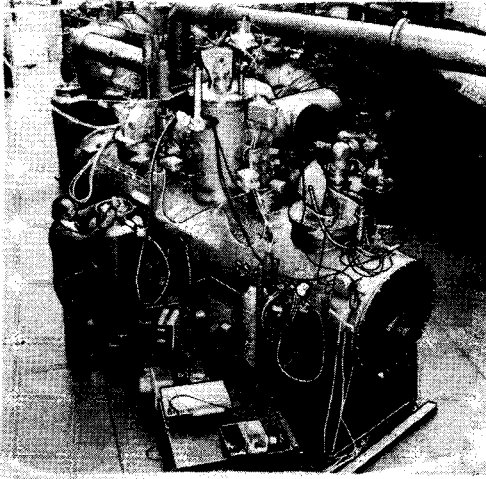


Fig. 5.

The cryostat for one deflector of the rf separator

TABLE IV

Parameter of the rf separator

Operating frequency	286 5	MHz
Operation mode	$\pi/2$	m
Length of deflector	2.74	m
Number of deflectors	2	
Number of cells/deflector	104	
Transverse voltage/deflector	3.3	MV
rf losses/deflector	30	W
Operating temperature	1.8	K
Q value	$>5 \times 10^8$	

4) Studies for e^+e^- Storage Rings

Large e^+e^- storage rings are much discussed presently. Since the energy loss of particles with the energy W goes at fixed radius like W^4 , the compensating electric fields E have to go like E^4 and hence the power loss in the cavities like E^8 . This turns out to be the limiting factor for the concept of storage rings since tens of MW of rf power are involved. One can put two kinds of questions.

- a) Given the radius of the storage rings, the total length available for acceleration and the total power available, how much can be gained in final energy by replacing normal conducting by superconducting cavities? The answer is given in fig. 6 for the example PETRA.

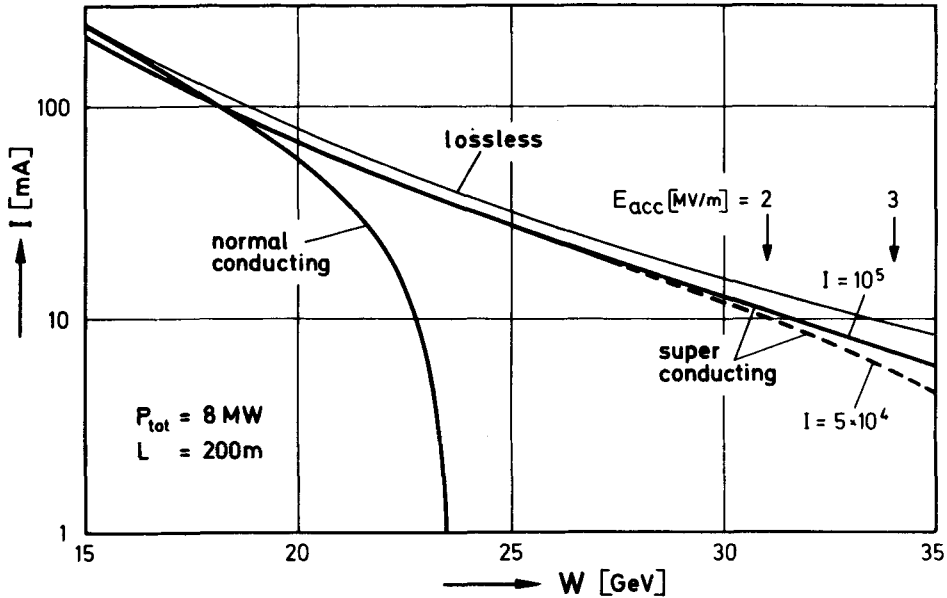


Fig. 6. Circulating current I versus final energy W for PETRA in the case of a fixed power P_{tot} available. In the case of normal conductivity, rf power is shared between the beam and the losses in the cavity walls. In the case of superconductivity power is shared between the beam and the refrigerator. Limitation occurs in this case due to the accelerating fields sustained in the resonators.

b) Given a radius and a final energy. How much can the construction and the operation cost be reduced by using superconducting instead of normal conducting cavities? The answer for the case of LEP is given in tables V and VI.

TABLE V

Parameters for normal-conducting (nc) and superconducting (sc) version of LEP (2 x 100 GeV)

	nc	sc		
		optimistic	pessimistic	
Peak voltage	1.73	1.73	1.73	GV
Accelerating field	0.6	3	2	MV/m
Cavity length	2.8	0.577	0.865	km
Beam power	44.2	44.2	44.2	MW
Cavity dissipation	53.7	0.0026 (IF = 10 ⁵)	0.0035 (IF = 5 · 10 ⁴)	MW
Total rf power	103.5	49.8	49.8	MW
Cryogenic losses (5 W/m)	-	2885	4325	W
Cooling power	-	6000	8500	W

TABLE VI

Cost comparison for normal-conducting (nc) and superconducting (sc) version of LEP
(2 x 100 GeV)

	nc	sc		
		optimistic	pessimistic	
Cavity	18	24	24	M\$/km
Accessories	17	17	17	M\$/km
Cryostat	-	18	18	M\$/km
rf power	0.9	0.9	0.9	M\$/MW
Cavity	98	24	35	M\$
Cryostat	-	10.5	16	M\$
rf power	96	46	46	M\$
Refrigerator	-	5.5	6	M\$
Total	194	86	103	M\$
Total ac power	148	77	80	MW

Cavities suitable for this application are under study at present at Karlsruhe, in collaboration with CERN and DESY.

In conclusion I would like to summarize by stating that rf superconductivity, after a period of over-optimism has met with some unexpected limitations mainly in the field strengths obtainable and resulting in a spell of undue pessimism. Because of the great promise of this technology research has to go on in two directions:

- a) How to build useful and reliable devices respecting the field limitations known presently and
- b) how to improve surface materials and to lift the field limitations by basic research on their causes.

We intend to pursue both lines at Karlsruhe.

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ДИСКУССИЯ

M.A.Allen: 1. Please, comment on the considerations which you have given to the interactions of the stored beam in storage rings with higher order modes in RF superconducting cavities.

2. In the 1 MW assigned for refrigerator did you take into account the higher order mode losses in the cavity walls?

A.Citron: 1. The higher order mode losses were, of course, one of our first concerns. We think that we can prevent them from loading the refrigerator by coupling them on to a sink at higher temperature (N₂ or room temperature). This requires a wide band coupler and a high pass filter that retains only the operating mode.

2. In this way the loading of the refrigerator due to higher order modes is negligible compared to ground mode losses and cryogenic losses (the latter were assumed to require 1 MW of refrigerator power).

В.Б.Степанов: Какова нестабильность разности фаз между двумя сверхпроводящими резонаторами линейного ускорителя и какими средствами она поддерживается в заданных пределах?

A.Citron: I talked little about the linac, but its phase control works like this: a master oscillator provides a standard phase, from which the reference phases are derived for every resonator by phase shifters. Those reference phases are compared to the phases of the field in the resonator and the phase error is

used to act on a fast tuner. This is a coaxial line coupled to the resonator and terminated by branches, that can be short circuited by diodes. The number of diodes closed, or more precisely the duty cycle when they are closed, determines the effective length of the coaxial line and thus the resonant frequency of the resonator. By acting on the resonant frequency the phase is adjusted to $\pm 0.5^\circ$.

G.A.Loew: 1. Have you considered the losses due to coupling large powers such as 8 MW into the storage ring structures?

2. Is anybody working on the possible beam instabilities that might arise from the fact that the RF cavities in the case of superconductivity will have a long memory?

3. What happens to your structures in case of a vacuum failure, do you have to rebake or reprocess the cavities?

A.Citron: 1. We have some experience with coupling large power into a S.C.structure from the linac, that is supposed to accelerate 0.5 mA. By carefully designing from the radio- and cryotechnical point of view, the coupling large power can be handled with losses comparable to the wall losses.

2. I'm not an expert on storage ring beam dynamics. You should keep in mind, though, that the electrical Q of the cavities due to the strong overcoupling is by no means excessively high compared to a normal one.

3. A bad vacuum failure exposing cold structure to lab. air makes reprocessing necessary. The simplest is an oxy-polish, anodizing the surface and subsequently removing the oxide. Next is a chemical or electrical polish. A rebake is the strongest measure.

F.Tazzioli: You mentioned studies of resonators suitable for storage rings, but you did not talk about them. Please do.

A.Citron: I did only mention these studies since they were started only recently, and no results can be reported. I mentioned the Alvarez structure operated at 720 MHz. We also have made iris structures at the same frequencies and they are being used for the first tests, while we are designing and building 500 MHz structures.

F.Netter: Concerning heavy ions postacceleration at a tandem Van de Graaff accelerator, do you believe that it is a definite advantage to choose the superconductive solution?

A.Citron: The answer is yes. The running cost, which is dominated by the power bill, is reduced by a factor of the order of five. Even if cost of maintenance of the refrigerator is taken into account, a large saving in running cost remains. The capital investment is not higher than for a conventional solution. So all one needs is a little courage to apply a new technology.