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INVESTIGATIONS OF SUPERCONDUCTING HELIX RESONATORS FOR A HEAVY ION POST ACCELERATOR

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Summary

As a part of a feasibility study the design and the construction of an accelerator section to be tested at the heavy ion beam of an electrostatic tandem Van de Graaff has been started. This test section consists of a cryostat with two independently phased λ/2-helix structures at 108 MHz and of a suitable rf-control system. Design criteria and recent results of measurements on a superconducting test cavity with electric surface peak fields up to 29 MV/m are presented.

Introduction

Rapidly growing interest in heavy ion research has led to an increasing demand for post accelerators to expand the capabilities of existing nuclear physics facilities. In particular superconducting linear accelerators may offer an attractive possibility for CW operated energy boosters with only moderate power consumption.

For the upgraded Heidelberg MP-Tandem Van de Graaff the installation of a rf post accelerator for ions up to mass 80 is considered. In a first project study[1] a basic layout of a possible post accelerator for that purpose consisting of superconducting helically loaded resonators has been discussed. Costs for construction and operation were estimated and open technical and physical problems were analysed. Superconducting helix resonators have been chosen as extended experience on this kind of accelerator structure is available from previous work in Argonne[2], Caltec[3] and Karlsruhe[4]. The study results in the conclusion that it would be worthwhile to construct and test an accelerator section of two superconducting resonators and to operate them under realistic conditions at the place of its possible installation using the pulsed heavy ion beam of the Heidelberg MP-tandem for test measurements. The results of these tests should give the basis for a comparison with other rf structures of recent design and provide reliable figures for a final proposal. Consequently a research and development program has started in collaboration between the institutes of Karlsruhe (rf superconducting work) and Heidelberg (beam transport and injection).

As the flexibility of the accelerator with respect to different sorts of injected ions is one of the basic demands from the users point of view short helix structures with an electric length of λ/2 are chosen. Each structure can be phased independently and adapted easily to the different injection velocities.

Laboratory tests[2,4,5] have indicated that no fundamental problems remain to be solved. However, problems related to the reliability in routine operation under realistic conditions of a superconducting accelerator have not yet been thorougly investigated. In particular, for a final proposal more precise answers to the following questions are needed:

- average accelerating field maintained during long term operation,
- degradation of superconducting surfaces by radiation,
- frequency perturbation due to mechanical vibration,
- necessary cooling power per accelerating unit,
- feasibility of forced flow normalfluid helium as a coolant.

Cavity design and model measurements

Choosing the geometry of the helix accelerator cavities the following criteria have to be considered:

The structure has to accelerate effectively all ions with the velocity from β=6% (≙ 1.77 MeV/A, the energy of $^{79}Br^{+26}$ as delivered by the MP accelerator) up to β=11% (≙ 6 MeV/A, the minimum desired final energy for ^{79}Br).

The frequency has to be chosen in order to synchronize with the newly installed subnanosecond beam pulsing system at 6.76 MHz on the Heidelberg MP accelerator and with the 108.48 MHz rebuncher under construction[6].

Particular care has to be taken to reduce the mechanical vibrations influencing the eigenfrequency of the helix resonators and therefore creating severe regulation problems.

The experiences with superconducting cavities have shown that lower rf-losses and higher field strengths are achievable more reliable for small resonators than for larger ones, presumably because of less difficulties with the surface treatment. Peak electric surface fields of up to about 30 MV/m have been reported[2,4] for such short helix resonators, corresponding to an accelerating field on the axis of about 4 MV/m.

As field emission of electrons seems to be the final limitation (see below), for the optimization of the resonators the electric peak surface field E_p was considered as an essential parameter and consequently it was tried to find a geometry which gives optimum energy gain for a given E_p. The optimization was carried out as follows: Starting with a modified sheeth model[7,8] the ratio of the peak electric surface field E_p to the accelerating field was minimized. These calculations are valid for infinitly long helices only, because end effects are neglected. They gave, however, a set of starting parameters which were used for building models. To take into account the influence of the finite length effects the field distribution of these models was measured with the perturbation method, and the energy gain and a transittime factor was calculated as a function of particle energy. With these experimental values the parameters were corrected to get a maximum energy gain for $^{79}Br^{+26}$ in the energy range between 1.77 MeV/A and 6 MeV/A.

Fig. 1 shows for two different helix tube diameter d=0.8 cm and d=1.0 cm the maximum accelerating field as a function of the radius of the helix as calculated with the modified sheeth model. With regard to the results on superconducting helix resonators (see below), the numerical values herein refer to a maximum tolerable electric surface peak field of E_p=16 MV/m. The accompanying magnetic peak field is still less than 62 mT, which seems to be sufficiently far enough from fields causing magnetic breakdown[2,4].

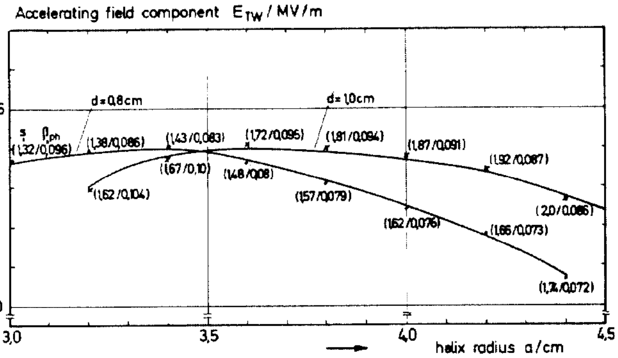

Fig. 1: Maximum obtainable accelerating field strength limited by electric surface peak field Ep=16 MV/m as a function of helix radius for tubes with a diameter of 0.8 cm (•) and 1.0 cm (×). s=pitch of the helix (cm), β_{ph}=v/c=phase velocity.

Fig. 2 gives the energy gain per charge unit of an ion with a charge to mass ratio Q/A≈0.3 as a function of the incident energy as calculated from the field measurements on resonator models. The parameters of the models are summarized in Tab. I. The higher energy gain for a helix from a 1.0 cm tube in comparison with 0.8 cm results from the greater length of the helix. For a total effective accelerating voltage of 13 MV about 50 units are needed. Calculations and model measurements show that the number of resonators could be reduced to about 30 or 35 if λ-cavities at 108 MHz or λ/2-cavities at 54 MHz were used. Enhanced vibration and more complicated surface treatment for longer structures, however, has led to the decision to choose λ/2-resonators at 108 MHz. In order to examine the properties of a λ-cavity separate tests are made on laboratory scale.

Tab. I: Parameters of λ/2-helix resonators at 108 MHz

	Cu-model 1	Cu-model 2	accelerating Nb-model	Nb-test cavity at 106 MHz
diameter of the helix 2a [cm]	6,52	6,55	6,7	6,52
diameter of the outer can 2b [cm]	16,4	16,4	15,0	13,0
diameter of the Nb-tube d [cm]	0,8	1,0	1,0	0,8
pitch of the helix s [cm]	1,36	1,6	1,65	1,36
number of winding n	10	10	~10	10
total length of the resonator L [cm]	26,5	29	29,6	29
$(E_{TW}/\sqrt{P_{\lambda/2}\cdot Q})$ sheeth model $[\frac{MV/m}{\sqrt{VA}}]$	$2,6\times10^{-4}$	$2,2\times10^{-4}$	$2,2\times10^{-4}$	$2,6\times10^{-4}$
$P_{\lambda/2}\cdot Q$ at $E_p \triangleq$ 16 MV/m [VA]	80×10^6	108×10^6	113×10^6	71×10^6
maximum energy gain [keV] per charge unit for optimum phase with $E_p \triangleq$ 16 MV/m	274	313	—	—

Fig. 3 shows the design of the chosen λ/2-resonator. The essential parameters are summarized in Tab. I. The dimensions of the outer tank have been chosen to avoid additional field enhancement at the helix surface.

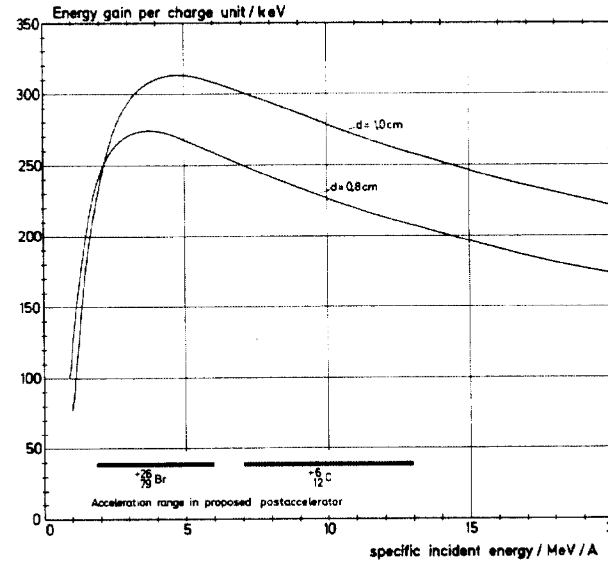

Fig. 2: Energy gain per charge unit as a function of the incident specific energy for the λ/2 model resonators at 108 MHz for the optimum phase. d=tube diameter.

The rf-power is coupled by a superconducting capacitive probe. A second superconducting coupling is provided for the fast electronic tuner. A movable Nb-plunger allows slow tuning of the resonant frequency by about ± 100 kHz. Field enhancement on the helix surface was measured to be less than 4% for this tuning range. To simplify the fabrication of the cavity TIG-welding instead of electron beam welding shall be used. First results with this technique are promising.

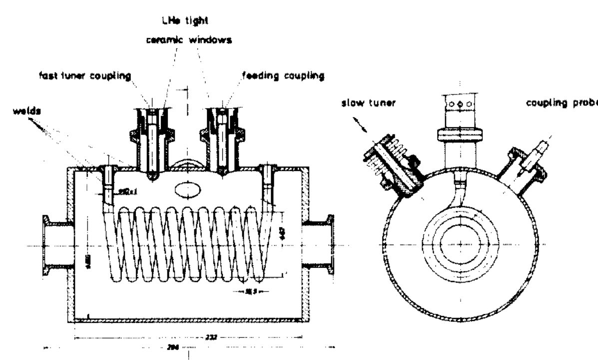

Fig. 3: The designed λ/2-Nb-helix resonator at 108 MHz (all dimensions are in mms)

Rf-control system

The rf-control system for the test section is similar to the system used for the superconducting proton accelerator.[5] The main difference results from the small beam loading due to the ion current of up to 1 µA only. Therefore the most important rf-power consumption occurs in the fast frequency control system.

With about 100 W rf-power a maximum tuning range of 2 kHz will be realized for a resonator with a reactiv power up to 2×10^8 VA. Based on measurements on models we expect markedly lower eigenfrequency deviations due to mechanical vibrations.

The design specifications for the control system are an amplitude error of less than 0.5% and a phase error of less than 1 degree. The internal stability of the three control loops implies a static loop gain of 90 dB for the amplitude loop, while the necessary loop gain in the two phase control loops is relatively moderate (50 to 70 dB).

Cryostat and methods of cooling

With respect to rf-superconductivity it is possible to run low frequency Nb-structures equally well at about 1.8 K (superfluid helium) and at 4.2 K, because the rf-losses and the critical fields do not change markably in this temperature range. First laboratory tests showed, that a forced cooling of a helix resonator with 4.2 K helium is possible without any instabilities causing additional vibrations. To get more experience with the forced cooling the cryostat was constructed[9] to be operable with superfluid helium as coolant as well as with forced flow of 4.2 K helium. For cooling with superfluid helium the additionally intended application of superfilters (fine porous material) enhances the colling capacity by a factor of 2 to 3 compared with resting superfluid helium[10].

Particular care was taken to isolate the accelerating elements against mechanical vibrations from the environment.

Results of measurements on a superconducting test cavity at 106 MHz

Recently a series of measurements has been done on a new helically loaded Nb-cavity. The parameters are summarized in Tab. I. A sequence of several treatments like electropolishing[11], oxypolishing[11], anodizing and annealing was carried out. In Tab. II some of the results are summarized.

Tab. II: Results of some measurements on a superconducting helix resonator at 106 MHz

test number	temperature T	Q_0 low field	Q_0 at maximum field	maximum acc. field E_{TW}	surface treatment and comments
no.	K	10^6	10^6	MV/m	
2	1,5 4,2	3090 1210	282 250	1,64 1,5	helix separately electropolished (about 50µ), then electron beam welded into the can, oxypolished, measured, electropolished (about 20µ) and anodized 400 Å
4	1,5 4,2	80 52	23 14	1,86 2,5	two times electropolished (each time about 25µ) and anodized 400 Å.
6	1,5 4,2	3630 1210	250 168	1,98 1,76	annealed in an UHV-furnace ($p<10^{-7}$ Torr) at 1100 °C for about 2h, oxypolished 3×1000 Å; bare metal surface.
8	1,5 4,2	4370 1240	— 1500 320 560	4,0 3,0 3,8 3,0	electropolished (about 20µ), bare surface. Limitation at high fields through electron field emission
9	1,5 4,2	1520 890	146 1100 —	3,9 3,0 —	anodized 400 Å. Limitation at high fields through field emission.

In the first runs maximum fields up to about $E_{TW}\approx2$ MV/m could only be achieved. This was probably caused by small areas with increased rf-losses, which induced the field breakdown. After additionally removing about 100 µm from the surface, the kind of breakdown changed and fields up to 4 MV/m were obtainable (test 8, 9 of table II). Now the field limitation was due to electron field emission effects. He conditioning[2] at a pressure up to about 2×10^{-4} Torr reduced the electron loading. Running the cavity for some hours under the remaining electron loading at $E_p\geq25$ MV/m increased again the loading effect and lowered the breakdown fields. A similar observation sometimes was made during He-conditioning at high fields. Charging effects in the surface oxydes caused by the emitted electrons or alternatively by the He-ions used for conditioning are thought to be the reason for the time dependent electron loading effects[12]. Another reason for the enhanced field emission may be caused by surface states due to adsorbed gases as discussed in ref. 13. A stable operation for more than 10 h was possible at $E_p\approx22$ MV/m without any increase of electron loading. Together with results of previous measurements[2,4] at present 16 MV/m seem to be a reasonable compromise for a design of a machine with a large number of acc. structures.

Conclusions

A test section consisting of a cryostat with two λ/2-helix accelerating structures operating at 108 MHz and a suitable rf-system has been designed and is under construction. At the turn of this year measurements are planed on the beam line of the MP tandem at Heidelberg.

With an optimized helix structure an energy gain up to about 300 keV per structure and charge unit can be obtained for electric peak fields on the surface $E_p\leq16$ MV/m.

In recent measurements on a superconducting Nb-helix test resonator electric peak fields up to 29 MV/m were achieved after a sequence of surface treatments. He-conditioning was succesfully used for decreasing the electron loading effects. Together with previous results we are therefore confident to obtain peak surface fields of 16 MV/m routinely in the designed accelerating cavities.

References

1 H. Deitinghoff, H. Klein, M. Kuntze, J. E. Vetter, E. Jaeschke, R. Repnow
KFK-Bericht-2141 (Kernforschungszentrum, Karlsruhe, 1975)

2 R. Benaroya, B. E. Clifft, K. W. Johnson, P. Markovich, W. A. Wesolowski
Proc. of the 1974 Applied Superconductivity Conference, Chicago (IEEE MAG, 1975)

J. Aron, R. Benaroya, L. M. Bollinger, B. E. Clifft, O. Despe, A. H. Jaffey, K. W. Johnson, T. K. Khoe, J. J. Livinghood, P.J. Markovich, J. M. Nixon, G. W. Parker, W. A. Wesolowski,
Proc. of the Ninth Int. Conf. High Energy Acc., Stanford (SLAC, 1974), p. 159

3 G. J. Dick, K. W. Shepard,
Proc. of the 1972 Applied Superconductivity Conference, Annapolis (IEEE, New York, 1972), p. 649

4 J. E. Vetter, B. Piosczyk, J. L. Fricke
Proc. Lin. Acc. Conf. Los Alamos, 1972, p. 145

B. Piosczyk
KFK-Bericht-1991 (Kernforschungszentrum, Karlsruhe, 1974)

A. Brandelik, A. Citron, P. Flécher, J. L. Fricke, R. Hietschold, G. Hochschild, G. Hornung, H. Klein, G. Krafft, W. Kühn, M. Kuntze, B. Piosczyk, E. Sauter, A. Schempp, D. Schulze, L. Szecsi, J. E. Vetter, K. W. Zieher
Proc. of the Prot. Lin. Acc. Conf. Los Alamos 1972, p. 93

5 G. Hochschild,
KFK-Bericht-2094 (Kernforschungszentrum, Karlsruhe, 1975)

G. Hochschild, D. Schulze, F. Spielböck
IEEE Trans. NS-20, 3, 116 (1973)

6 A. Gomp, W. Hahn, E. Jaeschke, H. Kania, S. Papureanu, R. Repnow, P. Völlinger, Jahresbericht 1973, MPI für Kernphysik, Heidelberg

7 A. J. Sierk, C. J. Hamer, T. A. Tombrello
Part. Acc. 2, 149 (1971)

8 H. Klein, N. Merz, O. Siart
Part. Acc. 3, 235 (1972)

9 The cryostat was constructed by H. Katheder, L. Schappals, IEKP, Karlsruhe

10 G. Krafft
private communication

11 H. Diepers, H. Martens, O. Schmidt, K. Schnitzke, Y. Uzel
IEEE Trans. Vol. NS-20, 3, 68 (1973)

12 J. Halbritter,
Part. Acc. 3, 163 (1972)

13 H. A. Schwettman, J. P. Turneaure, R. F. Waites
J. Appl. Phys. 45, 2, 914 (1974)