The Superconducting Cavities for the TRITRON *

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Abstract

The Tritron is a separated orbit–cyclotron with superconducting magnets and rf–cavities . The six cavities operate at 170 MHz. They are fabricated by electroplating copper onto fibreglass shells. The copper is electroplated with PbSn as superconductor. Test results are given. The accelerating voltage and the quality factor Q lie above the design values. The highest gap field reached was 10.6 MV/m.

I. INTRODUCTION

The Tritron is a feasibility study of a new type of cyclotron, a superconducting separated–orbit cyclotron with a MP–tandem as injector [1,2]. It will increase the ion energies by a factor of ≈ 5. The ion beam is guided by narrow superconducting window–frame magnets along a spiral orbit with almost 20 turns [3]. Radially neighbouring channel magnets are joined into 12 flat sectors (sector angle 20°). In each second intermediate gap (sector angle 10°) a superconducting accelerating cavity is inserted (see fig.1). The magnets and cavities hang inside a common vacuum vessel below a ring shaped liquid–helium reservoir. There is no separated vacuum chamber for the beam. The resonators are cooled indirectly with pipes. The operating temperature is between 4.5 K and 5 K. The present paper reports the development of the superconducting cavities.

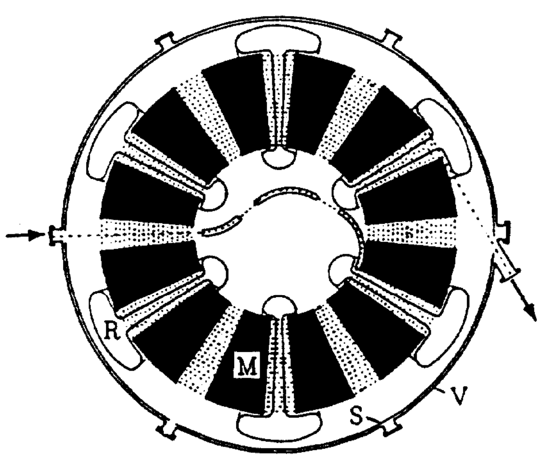

Figure 1: Horizontal Tritron cross section: resonator (R), magnet sector (M), vacuum tank (V), cooling shield (S)

II. CAVITY DESIGN AND FABRICATION

The six cavities of the reentrant type are operated in the fundamental mode at a fixed frequency of ≈ 170 MHz, corresponding to harmonic numbers of ≈ 20 to ≈ 60. Each cavity accelerates 20 parallel beams in the same gap. The gap walls have 20 beam holes (ϕ 13 mm) at the distance of the turn separation $\Delta r = 40$ mm. To obtain the rather large turn separation, high voltage amplitudes in the cavities are needed, at least $U_1 = 250$ kV at injection and $U_{20} = 530$ kV at extraction. The design value for the dissipated heat per cavity was fixed to 6 W. The maximum total beam power is expected to be ≈ 1 kW, so each cavity has to transfer ≈ 170 W.

The gap width of the cavities should be as large as possible within the limits set by the transit–time factor, to keep the maximum electric field as well as the dissipated heat small. It was chosen to be 62 mm at the first beam hole and to increase linearly to 128 mm at the last, resulting in an almost constant transit time factor. The gap length is about 900 mm, the effective height 150 mm. The cross section for the magnetic rf–flux has to be large in order to get a nearly constant electric field in the gap and small magnetic surface fields. The total radial length of a cavity is 1233 mm (see fig.2). In the fundamental mode no currents will cross the horizontal plane if the horizontal symmetry is perfect. Therefore each resonator is made out of two halves, which are connected simply by a flat joint.

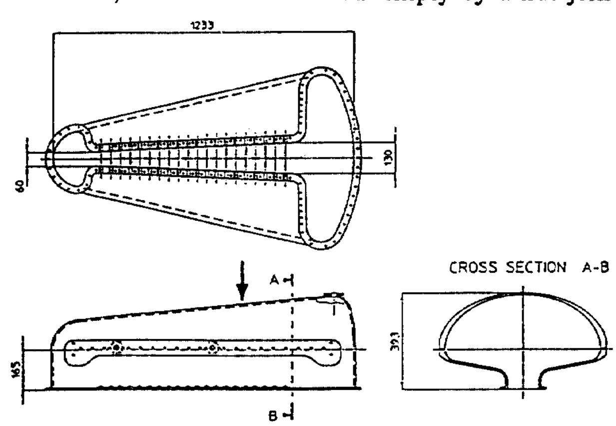

Figure 2: Cross sections of the upper half of a Tritron cavity. Top: cross section in the plane of the beam orbit. In this plane the halves are connected by a flat joint. Numbers in mm.

To get a small field enhancement factor E_{peak}/E_{max}, the curvature of the accelerating lips is made large. E_{peak} is

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the maximum electric field on the surface, E_{max} is the largest field in the gap. The concept of an accelerating voltage including the transit time factor is not used here because the range of the particle velocities will be quite large ($0.05 < \beta < 0.14$ at injection and $0.10 < \beta < 0.30$ at extraction). The 3-dimensional computer code Mafia [4] yields $E_{peak}/E_{max} \approx 1.2$, when the influence of the beam holes is neglected. To estimate the surface fields near the beam holes the 2-dimensional code Urmel [5] was used. An upper limit of 1.5 for E_{peak}/E_{max} was derived.

Compared with superconducting resonators for most other accelerators the Tritron cavities are quite large and complicated. Instead of Nb a thin layer of PbSn electroplated on copper is used. The good thermal conductivity of copper stabilizes heat producing defects on the superconducting surface. In addition pipe cooling (thermal siphon cooling) is possible, a bath–cryostat is avoided and the amount of liquid helium is reduced. The vacuum system is simple: beam and insulation vacuum are one. To avoid problems with ponderomotoric oscillations and the frequency tuning system, the cavity has to be free from vibrations. Therefore a minimum wall thickness of 10 mm was chosen. To produce the 12 cavity halves, copper is electroplated onto fibreglass shells. 12 shells were needed, because each shell had to be destroyed to remove it from the cavity inside. All shells were fabricated in the same demountable mold to keep differences between the single cavities small. In a distance of 165 mm from the symmetry plane on both sides of each cavity half holes and threads are drilled for adjustable coupling probes and for fixing the cooling pipes with screws. Each cavity has a mass of $\approx$ 450kg.

The superconductor PbSn is used instead of pure lead because of its enhanced stability against chemical reactions, its lower BCS–resistance and its better throwing power during the electroplating procedure [6]. The critical temperature of the PbSn–alloy (4 atomic% Sn) was measured to be 7.5 K. The temperature dependent part of the surface resistance R_{BCS} is reproduced by the expression $R_{BCS} = 6.85 \cdot 10^{-5} f^{1.9} 1/T e^{-15.1/T}$ with R_{BCS} in Ω, f in GHz and T in K. Due to the rather low frequency of 170 MHz the cavity needs not to be cooled below 5 K. For PbSn at 170 MHz and 5 K, R_{BCS} is $2.3 \cdot 10^{-8}$ Ω, which would cause a dissipated heat of 0.55 W per cavity at U_{20} = 530 kV. If the residual resistance were 10 times larger than R_{BCS}, the resulting heat loss of 6 W per cavity would still be acceptable. To a heat loss of 6 W corresponds an unloaded quality factor $Q_o = 3.7 \cdot 10^8$.

The plating bath for electroplating the cavity halves with a 5μm thick layer of PbSn is commercially available (Slotolet KB, Schlötter GmbH, D–7220 Geislingen) [7].

III. RESULTS OF MEASUREMENTS

So far six complete cavities have been fabricated and electroplated with PbSn. The frequencies at T = 300 K of the cavities except the first one were almost the same: $\nu = 170.10 \pm 0.05$ MHz. The first cavity was slightly deformed during the production, resulting in a frequency of 169.34 MHz. The frequencies of all cavities can be adjusted by proper deformations.

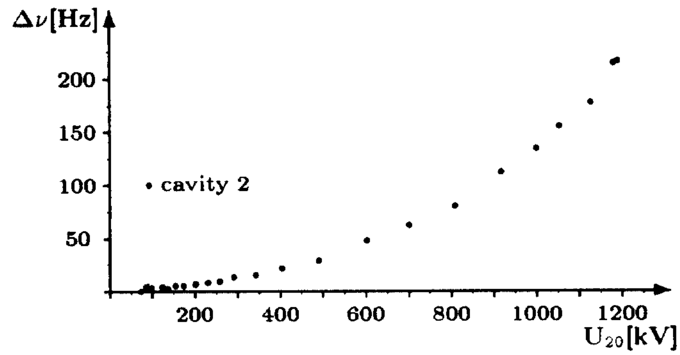

Figure 3: Frequency shift caused by radiation pressure versus the accelerating voltage at the 20th beamhole.

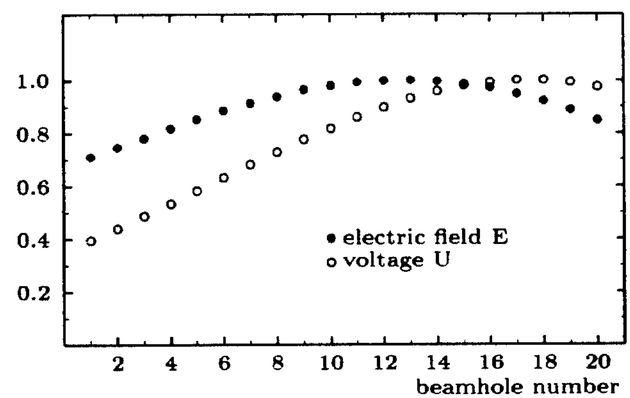

Figure 4: The characteristics of the normalized accelerating voltage U and the electric gap field E along the 20 beam holes.

When cooled down to 5 K the frequencies increase by $\approx$ 560 kHz according to the thermal contraction. At repeated cooling cycles the frequency of each cavity is reproducible within $\approx$ 8 kHz. Pressing the upper half of the cavity from above by 1mm (see arrow in fig.2) causes a frequency increase of 20 kHz. The tuning screw, which acts on a long lever–arm, can be turned from outside the vacuum vessel. The fine tuning will be made by quartz rods moved into the cavity volume at the foremost probe hole. The electronic phase control system is an adapted version of the system of S–DALINAC at Darmstadt [8].

Due to the stiffness of the cavity walls the frequency is rather stable. Frequency variations caused by acoustic noise stay within the scope of the electronic phase control system ($\approx$ 10 Hz). The lowest mechanical resonance frequency of the cavities is $\approx$ 170 Hz, measured at T = 300 K. The frequency increase due to electromagnetic pressure shows the expected quadratic dependence upon the gap voltage (fig.3). Even at this high voltage no ponderomotoric oscillations were observed.

Measurements of the unloaded quality factors of two cavities at 300 K before electroplating with PbSn gave $Q_0 \approx$ 25000. From this the geometry factor $G = Q_o \cdot R_s \approx 85\Omega$ results with R_s = 3.4 mΩ for the surface resistance of

OFHC–copper. The corresponding values Q_o and G calculated with the Mafia code are ≈ 10% higher. Fig.4 shows the relative distribution of the electric gap fields at the beam holes and the resulting characteristic of the accelerating voltages. They were obtained approximatively by moving a long saphir rod (diam.6mm) on the axis of the beam holes into the gap and observing the frequency shift (cavity No.3, without PbSn). From the voltage gradient at the first beam hole the maximum magnetic rf–field can be estimated: for $U_{20} \approx 1.2$ MV one gets $B_{rf} \approx 0.02$ T in agreement with calculations with Mafia. The absolute accelerating voltage at the 20^{th} beam hole was obtained with an accuracy of ± 15% by measuring the energy shift of conversion electrons from a Bi^{207} source.

Several test runs at $T \leq 5$ K were made with four cavities to investigate and to improve the unloaded quality–factor Q_o as function of the accelerating voltage in the 20^{th} beam hole U_{20}, respectively of the maximum electric gap field E_{max} (at the 13^{th} beam hole). No clean room was used for the assemblage of the cavity halves. The cavities were stored in laboratory air for months with the beam holes closed by adhesive tape only. Each cavity was opened for surface inspections at least once. Each was cooled down several times. When starting the cooling, the pressure was typically less than 0.02 Pa = $2 \cdot 10^{-4}$ mbar, and below 5K less than 10^{-5} Pa. The magnetic background field in the experimental hall was generally $\approx 8 \cdot 10^{-5}$ T, directed oppositely to the field of the earth.

All four cavities showed a similar behaviour. Every time a cavity was exposed to air, strong multipacting occured at low field levels with U_{20} of some kV. After some minutes of rf–processing this low–level multipacting disappeared. In addition high–level multipacting with U_{20} as high as 400 kV were observed.

For the first two cavities all multipacting could be removed. Then field emission was the limiting effect. Above voltages of some hundreds of kV γ–radiation was observed near the horizontal plane of symmetry. In case of the second cavity the distribution of the γ–ray intensity indicated, that the source was positioned near the 20^{th} beam hole. Generally each cavity was conditioned with helium during several hours, improving the maximum accelerating voltage by ≈ 40%.

In fig.5 the best results obtained up to now for the first four cavities are summarized. The cavities are numbered according to their production. The improvement of the Q_o values at least at low and medium voltages with the cavity number can be explained by the increasing experience in producing perfect PbSn–layers: the last two cavities had much less dark regions on the light gray coloured surfaces compared to the first and even to the second cavity. The cavity No.1 was electroplated with PbSn several times before. The result shown here is the first curve exceeding the design values at $U_{20} = 530$ kV and $Q_o = 3.7 \cdot 10^8$. The curve remained unchanged, when the magnetic background field was compensated to less than $\approx 10^{-5}$ T by a pair of circular current loops.

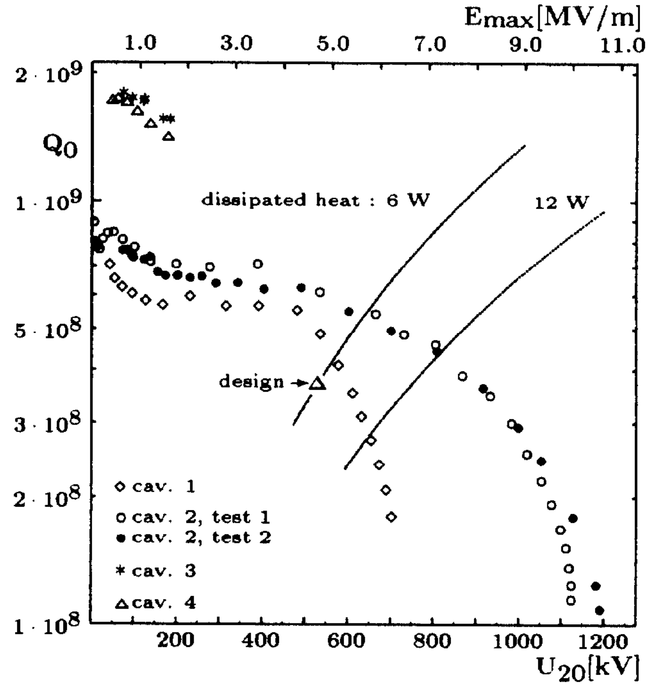

Figure 5: Unloaded quality factor Q_o versus the voltage U_{20} and the maximum gap field. Also given are lines of constant dissipated heat.

An increase of the background field to $\approx 5 \cdot 10^{-4}$ T lowered the Q_o–value from $\approx 5 \cdot 10^8$ to $\approx 1.8 \cdot 10^8$.

For the second cavity two test results are shown. The second curve with somewhat higher maximum voltage was measured four month after the first, indicating no degradation within this period. To the maximum voltage of almost 1.2 MV corresponds a maximum gap field of 10.6 MV/m. The dissipated heat at this high field level was ≈ 100 W (cw). The maximum temperature at the cavity outside was measured locally to be ≈ 6K. This demonstrates the excellent cooling conditions.

The third and fourth cavities have even better quality–factors at least at low voltages. Up to now the maximum voltages of both cavities are limited by high multipacting levels. Further tests are needed.

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