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OPERATION OF A SUPERCONDUCTING ACCELERATING CAVITY IN PETRA

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To investigate the feasibility of superconducting cavities in electron-positron storage rings a single cell Niobium cavity was tested in PETRA. The paper describes the experimental setup and summarizes the results obtained: Accelerating field gradients of 3 MV/m and Q-values of 10^9 are measured in an operating storage ring and maintained over many weeks. Synchrotron radiation impinging on the cavity surface did not affect the performance. Higher order modes excited by the beam were coupled out, their amplitudes agree with theory. PETRA was operated at 5 GeV and 2 mA with the superconducting cavity alone.

1. Introduction

The application of superconducting accelerating cavities in e^+-e^--storage rings has been considered by several authors $^{1-4}$. The aim was to save RF-power and thereby to reach a higher energy at reasonable costs. Whereas superconducting cavities have shown considerable performance in many laboratory experiments $^{5)}$, the question was open,whether the specific circumstances typical for storage rings would allow safe operation for extended periods of time.

In detail, the following questions were asked:

- Is it possible to achieve sufficiently high accelerating fields and Q-values in a storage ring and maintain this performance for a long time?
- It is possible to couple the high RF-beam power into the cavity avoiding excessive heat losses?
- Is it possible to couple the beam excited higher order mode power out to avoid excessive Helium losses and beam instabilities?

To answer these questions an experiment was carried through, where a single cell 500-MHz-Niobium cavity operating in the TM_{010}-mode was tested in PETRA. The results are summarized in this report.

At the same time a similar experiment was made at Cornell $^{6)}$. In February 1983 CERN started measurements on a 5 cell cavity at PETRA $^{7)}$.

2. Experimental Setup

The cavity had a cylindrical shape, 466mm diameter, 256mm gap-length with beam tubes of 200mm length and 120mm diameter. The basic parameters of the cavity are shown in Table I. The input coupling was designed to couple 100 kW of RF-power into the cavity. Two higher order mode couplers situated at an angle of 110^0 in the endplates reduced the Q-values of all modes above 500 MHz from $\sim 10^9$ to 10^2-10^4, while leaving the fundamental mode almost undamped. A tuner, acting by slightly moving the endplates, changed the frequency of the fundamental mode by ± 130 kHz.

The cavity was installed in a bath cryostat filled with Helium from containers via a Helium transferline.

A scetch of the cavity and the cryostat is shown in fig. 1.

A control- and interlocksystem, that allowed remote control and save operation of the cavity and the cryogenic system, was connected to the PETRA control system.

The RF-supply was done by a standard 500 MHz - 0.5 MW Klystron (Valvo) from DESY.

More details about the experimental setup are given in references 8 and 9.

TABLE I
Room temperature RF-parameters of the PETRA cavity

Parameter	value	Definition
Frequency MHz	500	$f = \omega/2\pi$
Vacuum wave length m	0.6	$\lambda = 2\pi c/\omega$
Shuntimpedance MΩ/m	22.5	$Z_{eff} = E^2_{acc} \cdot L/P_c$
Q-value	$4.18\ 10^4$	$Q_0' = \omega W/P_c$
Accelerating field gradient V/m	42.4 W	$E_{acc} = \frac{1}{L} \int_{-L/2}^{+L/2} E_z(z) \cos\frac{2\pi z}{\lambda} dz$
Geometry factor Ω	241	$G = Q_0 \cdot$surface resistance
Peak electric field ratio	1.93	E_p/E_{acc}
Peak magnetic field ratio mT/MV/m	3.63	B_p/E_{acc}

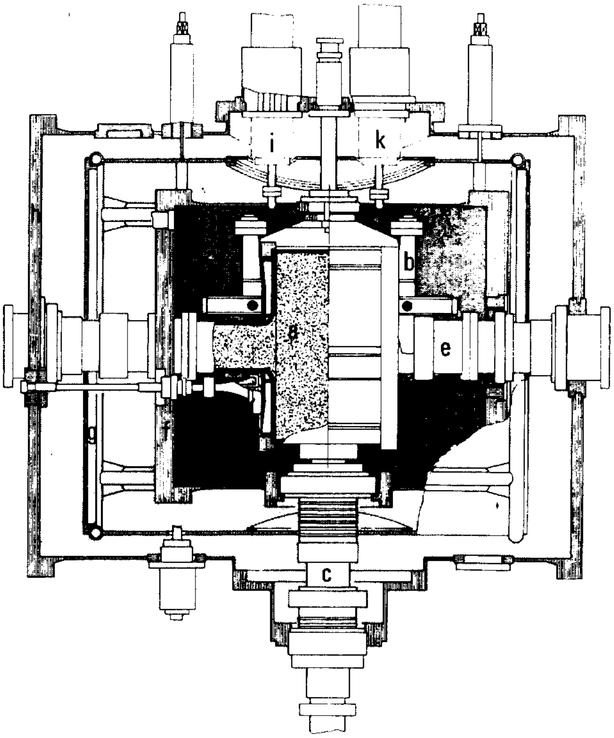

Fig.1: PETRA-Cryostat. a=cavity, b=tuner, c=input coupling, d=higher order mode coupling, e=beam tube, f=helium-tank, g=heat shield, h=outer tank, i= helium- and nitrogen supply, k=outgoing gas.

3. Experimental Results

3.1 Results Outside the Beam

Measurements in a vertical cryostat without input and higher mode couplers were reported in $^{10)}$. The best values achieved were E_{acc}=3.7MV/m and Q $=2\times10^9$ at 4.2 K and 4.3MV/m and 6×10^9 at 1.8 K. In the PETRA-cryostat with all couplers connected E_{acc}=2.5MV/m and Q=0.3×10^9 was measured. The field limitation was electron loading. At E_{acc}= 2MV/m the electron loading was negligible and Q was 1×10^9.

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3.2 Results on E_{acc} and Q in PETRA

After the assembly in PETRA the field and Q-measurement was repeated with the two beam tube valves outside the cryostat closed. Due to a window failure in the normal conducting part of the input coupler E_{acc}=2.9MV/m could only be measured for a short time. 2.3MV/m and Q=10^9 could be maintained throughout the whole experiment.

At E_{acc}=2.3MV/m the valves connecting the PETRA beam tubes to the cavity were opened - with no change of the cavity performance. The beam tests to be described below were carried through, and no change of E_{acc} and Q was observed at beam currents up to 4×5 mA and particle energies up to 18 GeV.

Since at the location of the cavity almost no synchrotron radiation was present, an orbit bump was generated, that set the beam about 1cm off axis and produced 1.5W of synchrotron radiation, which impinged on the cavity surface at a small area around the iris edge, where the electric field was high. It had no effect on the accelerating field gradient of 2.3MV/m.

3.3 Long Time Performance

After the first measuring period the cavity was kept at 4K with the RF supply switched off for six weeks, while the normal PETRA operation was continued. After this time E_{acc}=2.3MV/m and Q=10^9 was measured again. The cavity was then warmed up to 80K and kept at this temperature for 2 months. At the end of this period the current in PETRA was increased to 4×8 mA which destroyed the beam tube valves by heating due to higher order mode losses. When PETRA was then switched off the valves did not shut properly and the cavity was let down to dry nitrogen while it was still at 80 K.

As expected, after this mistreatment E_{acc}=0.07MV/m and Q=10^5 was measured. The cavity was then warmed up to +50°C and pumped for one day. During this time the broken window in the input coupler was replaced.

After cooling down to 4.2K again E_{acc}=3.15MV/m and Q=10^9 was measured. The field limitation was now thermal breakdown at the higher mode couplers.

3.4 Higher Order Modes

The difference in He-losses with and without beam was less than 1W even at the highest obtainable beam currents of 4×6mA. As expected, no beam instabilities produced by the single superconducting cavity in presence of 60 normal conducting ones were observed. Since the loaded Q of all higher modes was between 10^2 and 10^4 the pulse excited by one bunch decayed to almost zero within 2μs before the next bunch arrived.

Fig. 2 shows a typical spectrum excited by a single bunch of about 5mA as measured by a spectrum analyzer. In the lower curve the beam is centered on the cavity axis. The upper curve shows dipole-quadrupole- and TE-modes that are excited if the beam is off axis. By increasing the frequency resolution the single lines of the spectrum of the circulating beam are resolved. The envelopes of these lines are the modes excited in the cavity.

By adding the power contained in each of these lines the power coupled out in each mode could be evaluated. To obtain the total power deposited the power coupled out at both higher mode couplers and at the input coupler had to be summed up. For modes above the beam tube-cutoff-frequency some power was radiated through the beam tubes, which could not be measured. Many such modes were observed up to 3.5GHz. These modes did not couple well enough to the beam tube, but their amplitude was apparently small enough not to cause problems with losses or instabilities. Table II shows the results obtained with a single bunch of I=5mA. The measuring error is ±10%. The notation used is following ref. 11. The power deposited in each mode is $P=kI^2T_b$ with T_b=bunch revolution time. The factor k(V/ps) is evaluated from the measurements and for azimutally symmetric modes compared with Superfish-calculations of the shuntimpedance R by k=(ω/4)•(R/Q). Except for the TM_{022}-mode the agreement is within 20%.

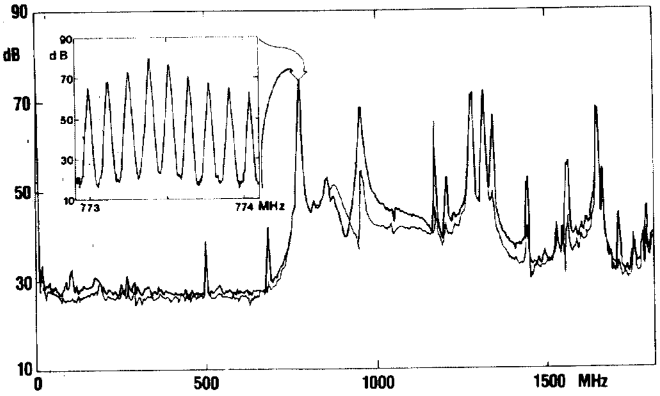

Fig. 2: Spectrum measured at one of the higher order mode couplers. Lower curve: beam on axis. Upper curve: beam off axis about 1cm, with dipole, quadrupole and TE-modes excited additionally. Insert: Abszissa spread out by a factor of 100 around 774MHz: The single machine lines, 130kHz apart, show the excited mode as envelope.

For the fundamental mode the voltage-built-up by successive bunches has to be taken into account. The cavity could be tuned to resonance or to antiresonance with the bunch, resulting in a maximum or a minimum excited voltage, respectively. Using the expression for the real part of the induced voltage 11) $V=\Delta V\cdot F_1(\tau,\delta)$ with $F_1(\tau,\delta)=(1-e^{-2\tau})/(2(1-2e^{-\tau}\cos\delta+e^{-2\tau}))$ and $\delta=(\omega_0-\omega)T_b$ (ω_0=cavity frequency $\omega=2\pi/T_b$, $\tau=(\omega T_b)/(2Q_L)$ the voltage ΔV induced in one passage could be evaluated and compared with the experiment. For $Q_L=4\cdot10^4$, which is set by the adjustment of the input coupling and R/Q=$(Z_{eff}\cdot L)/Q$ from Table I the numbers given in Table III can be evaluated. The agreement between measured and computed values is quite good.

For the total energy loss the BCI-program 12) gives a value for K_{tot}=0.297V/pC; this can be compared to the experimental value given by the sum of all single k's measured, which is 0.325V/pC.

TABLE III
Fundamental Mode excited by a 5 mA single Bunch of length σ_{rms} = 2 cm

		Theory	Measurement
induced voltage	ΔV_b[V]	4.87×10^3	5.37×10^3
voltage / charge	k [V/pC]	0.127	0.140
shuntimpedance / Q	R/Q [Ω]	161.6	178.1
F_1, resonance	F_1^{max}	3.343	3.272
F_1, antiresonance	F_1^{min}	7.87×10^{-2}	7.64×10^{-2}
voltage at resonance	V_{max} [V]	1.63×10^4	1.76×10^4
voltage at antires.	V_{min} [V]	3.83×10^2	4.10×10^2
power at resonance	P_{max} [W]	81.40	87.8
power at antiresonance	P_{min} [W]	1.916	2.05

3.5 Operation of PETRA with the s.c. cavity only

At an accelerating field gradient of 2.3MV/m and a gap length of 0.3m the voltage seen by the beam is 0.69MV. This is sufficient to substitute the energy lost to synchrotron radiation at 5GeV and the energy lost into higher order modes in the remaining 90m of normal conducting cavities. A total current of 2mA in 8 bunches could be stored.

4. Conclusion

The experiment has positively answered all questions mentioned above concerning the feasibility of superconducting cavities for storage rings:

- Accelerating fields gradients of 3MV/m and Q-values of 10^9 can be achieved in the environment of a storage ring and maintained for a long period of time.
- Synchrotron radiation does not affect the field of 2.3MeV/m obtained.
- A vacuum accident was cured by simply warming up.
- Except for a window failure the input coupling worked as expected.
- The higher order modes excited by the beam can be coupled out and behave according to theory.
- PETRA was operated with one superconducting cavity alone at 5 GeV and 2 mA.

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TABLE II

Higher order modes excited by a single bunch of 5mA (EK: power measured at the input coupling; HOM R, HOML: power measured at right and left higher order mode coupler. Bunchlength σ_{rms} = 2 cm.)

Mode	Frequ. MHz	HOM R mW	EK mW	HOML mW	sum mW	k_{exp} V/pc	$k_{theo.}$ V/pc
TE_{111}	681	16.2	4.5	13.1	33.8	1.76×10^{-4}	
	682	0.67	7.4	-	8.1	4.20×10^{-5}	
TM_{110}	769	785	2205	185.4	3176	0.0165	
	772	755	-	134.6	890	0.00464	
TM_{011}	774	8047	551	5119	13717	0.0714	0.0571
TE_{211}	858	-	9.2	-	9.2	4.78×10^{-5}	
TM_{111}	950	205.7	-	59.5	265.2	0.00138	
TE_{112}	1168	8.1	-	58.8	66.9	3.48×10^{-4}	
	1170	16.5	-	9.4	25.9	1.35×10^{-4}	
TM_{021}	1278	2969	172	1895	5036	0.0262	0.0288
TM_{112}	1309	1345	114	648.1	2107	0.0110	
TM_{012}	1314	2426	-	1438	3864	0.0201	0.0171
TE_{212}	1338	77.6	-	51.3	129	6.72×10^{-4}	
	1340	13.6	-	13.9	27.5	1.43×10^{-4}	
	1528	2.6	-	-	2.6	1.34×10^{-5}	
	1530	7.4	-	-	7.4	3.88×10^{-5}	
	1546	-	-	9.1	9.1	4.72×10^{-5}	
	1646	40.1	170	18.4	228.5	0.00119	
		12.5	42.7	58.6	113.8	5.92×10^{-4}	
TM_{022}	1651	1338	1974	1436	4748	0.0247	0.0469
	1666	-	20.4	38.8	59.2	3.08×10^{-4}	
	1784	18.5	83.5	16.8	118.8	6.19×10^{-4}	
	1825	54.2	19.8	59.6	133.6	6.95×10^{-4}	
	1826	191	19.2	45.4	255.9	0.00133	
	1878	-	10	37.3	47.3	2.46×10^{-4}	
	1956	-	-	3.5	3.5	1.83×10^{-5}	
	2083	-	58.2	-	58.2	3.03×10^{-4}	
	2091	18.5	-	29.6	48.1	2.50×10^{-4}	
	2293	-	-	2	2	1.05×10^{-5}	
	2356	-	-	18	18	9.37×10^{-5}	
	2386	-	-	9.3	9.3	4.84×10^{-5}	
	2388	-	-	7.3	7.3	3.82×10^{-5}	
	2391	-	-	9.1	9.1	4.74×10^{-5}	
	2412	43.2	-	22.6	65.8	3.43×10^{-4}	
	2439	63.4	-	10.4	73.9	3.85×10^{-4}	
	2500	-	-	5.9	5.9	3.08×10^{-5}	
	2502	-	-	10.8	10.8	5.64×10^{-5}	
	2535	71.1	-	27.1	98.2	5.12×10^{-4}	
	2537	24.3	-	15.3	39.6	2.06×10^{-4}	
	2538	-	-	4.4	4.4	2.31×10^{-5}	
Total (W)		18.6	5.5	11.5	35.6	0.185	0.170