PETRA-III
- Technical Design Report -

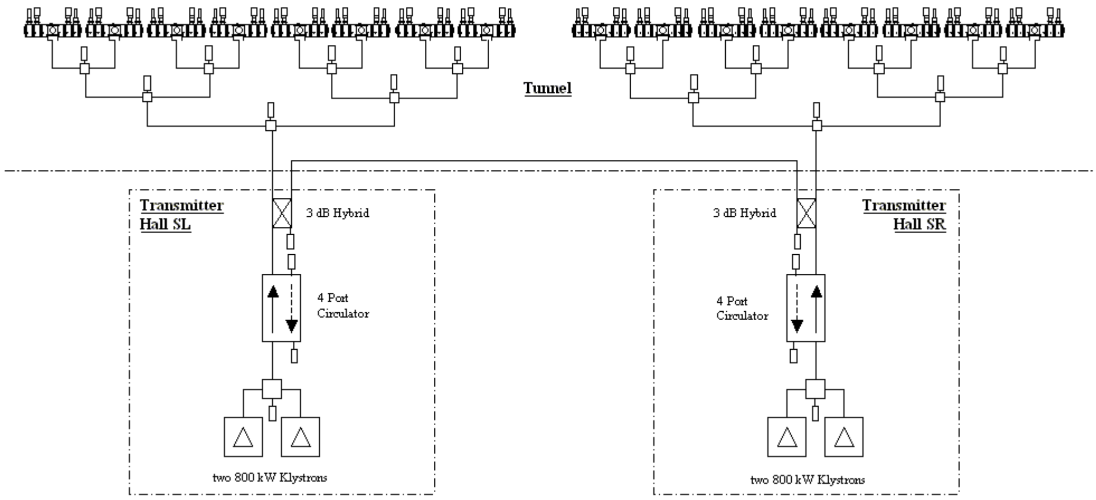
3.5 The RF System

3.5.1 Introduction

3.5.1.1 The existing PETRA-II RF System

PETRA-II is currently used as proton and lepton pre-accelerator for HERA. In addition it is used as a synchrotron radiation source for HASYLAB. Two 500-MHz rf systems with 1200 kW nominal output power each are installed. One rf system consists of two Philips klystrons for supplying eight normal conducting 7-cell cavities. The installed klystron types YK-1301 and YK-1304 are 800-kW tubes. This tube types are also in service at HERA and DORIS. The rf output power is limited to 600 kW per tube at PETRA due to the lower nominal voltage of the existing transmitter power supplies (58 kV instead of 75 kV). Both rf systems are running at 500 kW each in pre-accelerator mode at 12 GeV and 50 mA beam current. The cavity voltage is 9 MV per rf system. About 50% of the rf power is needed to compensate the synchrotron radiation losses. The other half generates the cavity voltage. It is possible to supply all 16 cavities by only one transmitter. For this case two 3-dB couplers and a 100 m waveguide line connecting both transmitters are installed**.** For switching to the so called "one-transmitter-mode" it is only required to insert two waveguide shorting plates at prepared places at the 3-dB coupler of the passive transmitter station. The "one transmitter-mode" is the preferred operation mode because of the lower energy consumption.

Fig. 1: The RF Systems of PETRA-II



3.5.1.2 Proposal for a New Transmitter System for PETRA-III

The proposed beam parameters of PETRA-III are 100 mA at 6 GeV with the option for a later upgrade to 200 mA beam current.
A total rf power of 1.3 MW is required for compensating the radiation losses of the damping wigglers, undulators, dipole magnets, cavity copper losses and the HOM losses. Furthermore a circumference voltage of 20 MV is needed for sufficient Touschek lifetime. The output power of the already existing rf systems would be sufficient for PETRA-III. But despite of

permanent technical modernization the basic transmitter components are meanwhile older than
25 years. Especially the high-voltage klystron supplies, crowbars, klystron-modulators, interlocks, low level rf, and control systems have to be renewed. From this point of view it was regarded to build completely new transmitters for PETRA-III. Even using of IOTs and other klystrons types were considered because of delivery problems of compatible klystron types in the past. The existing cavity system should remain. Due to the available manpower and budget and the tight schedule a new cavity system doesn't seem realizable until 2007.

3.5.2 Considered Transmitter Concepts

For comparing different transmitter concepts the prices of the essential technical components were determined. Potentially required civil constructions were not taken into account. Further conditions of investigation for the different transmitter concepts were:

1. Sufficient rf power for a possible later upgrade to 200 mA beam current.
2. Transmitter tube operation maximum at 80% of the nominal output power to increase the reliability.
3. Each rf system should drive the same number of cavities.

To study the expected reliability of the different transmitter concepts the rf systems were subdivided into 18 comparable units (transmitter-tube, high voltage power supply, circulator, cavity, rf-loads, fast interlock system, controlling, water cooling etc.). For each of these 18 subunits the trip and repair rates were determined. Trips and repairs of the 11 rf systems of HERA, DORIS and DESY were used as a data base. 470 events of 4900 transmitter operation-days have been analysed. The results are summarized in the following table:

Costs and Reliabilities for Different RF-System Concepts

Concept	**1**	**2**	**3**	**4**	**5**	**6**
Number of rf systems	2	2	4	4	4	16
Number and type of transmitter tubes per rf system	1x1,2 MW Klystrons without M.A. [1]	2x600 kW [2] Klystrons with M.A.	1x600 kW [2] Klystrons with M.A.	2x300 kW Klystrons without M.A.	2x300 kW IOTs	2x75 kW IOTs
Investments [3]	100%	100%	145%	155%	195%	185%
Operation costs [3], [4]	125%	130%	130%	140%	100%	115%
Investments & Costs for 10 years operation [3]	100%	105%	115%	125%	115%	120%
MTBTrip	6d	5d	4d	3d	2d	1d
MTBFailure	60d	30d	25d	30d	20d	8d

[1] M.A. = modulation anode
[2] 800-kW klystrons are not operated at nominal cathode voltage, therefore the power is limited to 600 kW rf power.
[3] Related to the cheapest concept
[4] Energy and tube costs for 300 Runs/a; 4000 operation hours/a; 40.000 h avg. tube life time

3.5.2.1 Comparison of Costs

The table shows that the concepts 1 and 2 are the cheapest because they consist of the smallest number of components. Additionally the two existing 4-MW circulators could be reused.
The concepts using IOTs are the most expensive although IOTs are about 30% cheaper than comparable klystrons. Since they are only available for less than 90 kW rf power at present they can not compete in costs with klystrons in the MW power range. 300-kW IOTs are considered in concept 5. The tube costs per kW rf power of such tubes would be quite attractive, unfortunately they are not state of the art at present. The additional costs for development, prototype tube and for generating some kW of drive power makes this concept

more expensive than the 300-kW klystron concept which was considered for comparison reasons.
One large advantage of IOTs is the 10% higher efficiency compared to klystrons. Further more the efficiency is quite constant over a wide output power range. Due to the operation costs the 300-kW IOT concept would be the most recommend. But the period required for investment amortisation by the smaller operation costs is longer than 10 years. Regarding investment and operation costs over a period of 10 years the concepts 1 and 2 are the most cost-effective.

3.5.2.2 Comparison of Reliability

Reliability of a facility decreases with the number of installed power components. In first approximation one can assume for instance that four 300-kW tubes cause four times more trips than one 1.2-MW tube. This applies also to high power supplies and all essential subsystems. Therefore the concept 6 is that one with the lowest expectable reliability. On the other hand the beam operation would be only affected if more than 3 rf systems are out of order at the same time. Nevertheless beam loss is probable not avoidable in case that just one of the 16 systems trips.
Due to the smallest number of installed power components the highest reliability can be expected for the concepts 1 and 2. However, in case of serious trouble with one of both rf systems only restricted beam operation is possible.

3.5.2.3 Conclusion

Concepts 1 and 2 are the cheapest and the most reliable. Concept 2 has the additional advantage that it is very similar to the existing PETRA-II installation and therefore it takes the minimum effort to renew the system. At HERA eight rf systems of this type have been operated successfully for several years.
In the following only concept 2 is considered in more detail.

3.5.3 The Preferred RF System Design for PETRA-III

3.5.3.1 Design Criteria

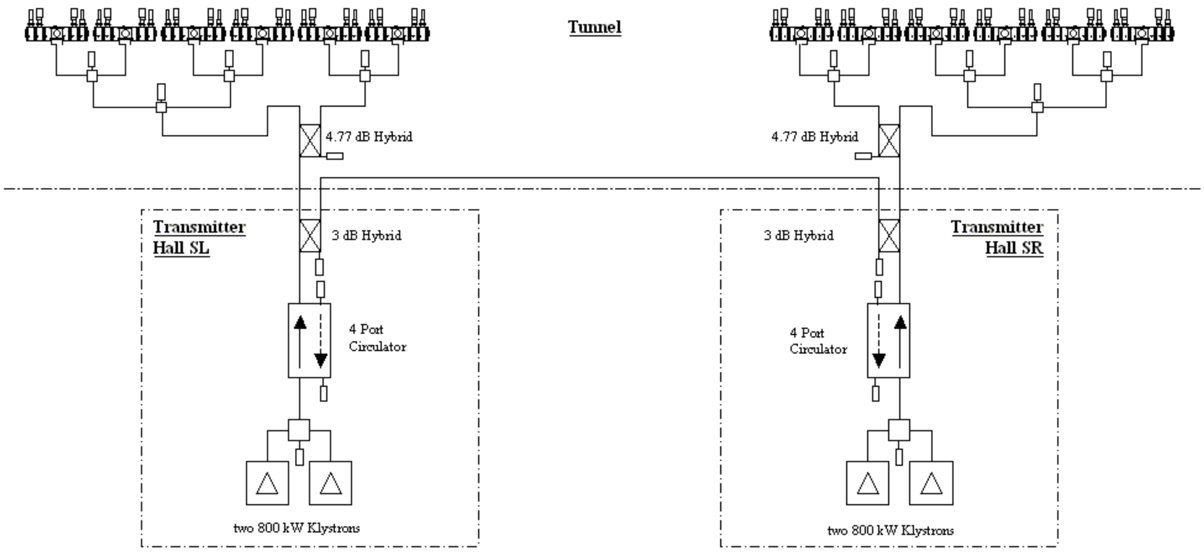
The preferred rf system for PETRA-III can be very similar to that of PETRA-II. For increasing the beam stability it is planned to reduce the shunt impedance by reducing the number of cavities. The minimum possible number of cavities is a compromise between the maximum transferable power per coupler and the maximum storable beam current with only one of both transmitters in service.
The maximum reliable power capability of an input-coupler is about 150 kW. This limit was chosen due to long time experience in this power range. In principle the so called PETRA-coupler is able to transfer much more power [1]. A power limit, caused by the design, is not known at present. Once, a coupler was tested up to 800 kW to find out the absolute maximum power capability. The test was stopped due to the limited maximum available power of the test-transmitter.
The maximum storable beam current is limited by the available rf power. The nominal power of each transmitter could be 1600 kW provided that the transmitter power supply is laid out for nominal cathode voltage of the used klystron type. In case of loss of one transmitter the remaining available rf power for beam operation is 1440 kW (in consideration of 5% safety margin and 5% transmission loss). This rf power would be sufficient for unlimited beam operation in case that all 16 cavities are left in the machine. Reducing the number of cavities to 14 would limit the storable beam to 97 mA. Concerning the maximum power capability of

the input couplers a reduction from 16 to 12 cavities would be possible. In this scenario the maximum storable beam current would be limited to 83 mA in the “one transmitter mode”. If operational experience will show that the input couplers are working reliable, a further cavity reduction to 10 could be envisaged in order to reduce the shunt-impedance further. At present it is preferred to reduce the number of cavities to 12, because of the higher storable beam current in the “one transmitter mode”.
Coupler power, transmitter power at normal operation and maximum beam current in “one transmitter mode” are shown in the following table for different cavity numbers.

Required RF Power and Maximum Beam Current versus Number of Cavities Installed

Number of 7-Cell Cavities installed	Coupling Factor for Matching @100mA	Power Transmission per Coupler [kW]	Required Transmitter Power @ 20MV, 100mA [kW]	Max. Beam Current with one Transmitter @1440 kW [mA]
2 x 8	2.4	81	2 x 690	107
2 x 7	2.2	99	2 x 731	97
2 x 6	**2.0**	**124**	**2 x 786**	**83**
2 x 5	**1.9**	**163**	**2 x 863**	**63**
2 x 4	1.7	230	2 x 978	31

Fig. 2: Modified RF System for PETRA-III

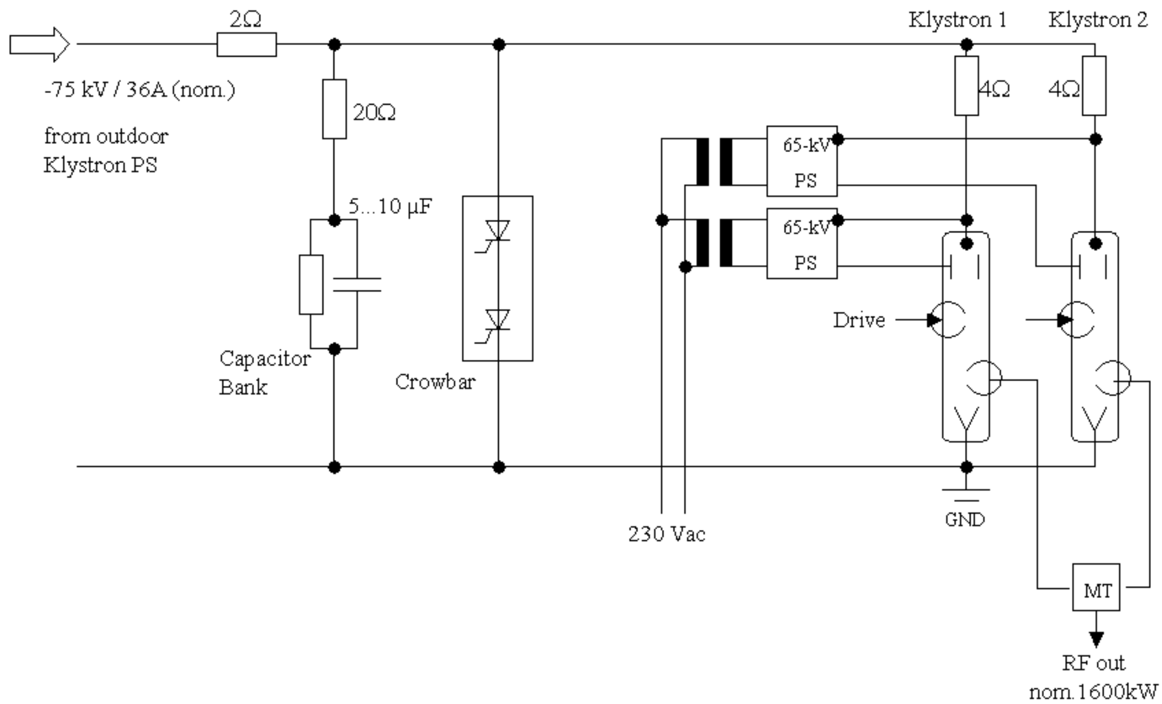


The existing rf systems can remain in their basic structure, as mentioned in **3.5.1.2**. However, high-voltage klystron supplies, crowbars, klystron-modulators, interlocks, low level rf, and control systems have to be improved and renewed.
For further information about high-voltage klystron supplies and crowbar systems see chapter **3.14.3 Transmitter Power Supplies**.

3.5.3.2 High Voltage Supply of the Klystrons

The 500-MHz klystrons of the 13 transmitters at DESY are equipped with modulation anodes. Therefore it is reasonable to use this klystron type for PETRA-III as well. However this requires additional modulation anode supplies. Having the possibility to operate different klystron types of different suppliers an independent modulation anode power supply for each klystron is necessary. For driving the modulation anodes fibre link controlled 65-kV power supplies are foreseen. DESY has long time positive experience with this kind of driving klystron modulation anodes.

Fig. 3: High Voltage Supply of the Klystrons

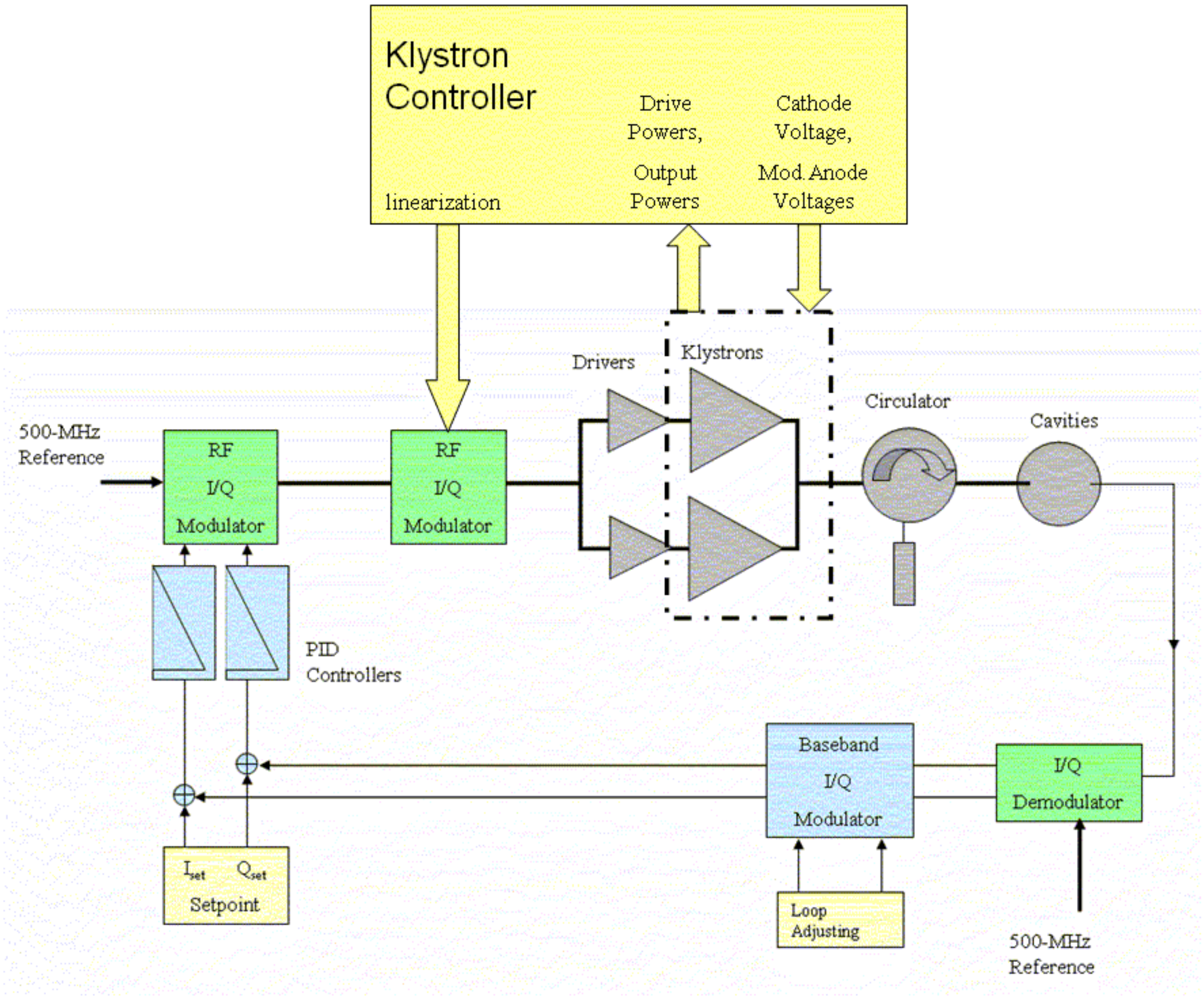


3.5.3.3 RF Controlling

Cavity Voltage Control Loop

The cavity voltage loop controls phase and amplitude of summed cavity voltages of one cavity system. The loop acts on the klystron drive. Instead of common used phase and amplitude control loops the higher performance of IQ control loops will be used [2]. It is foreseen to keep the klystron efficiency at maximum by controlling cathode voltage and current as a function of klystron output power and klystron drive. A klystron controller algorithm is under development.

Fig. 4: Controlling the RF Systems



Cavity-Tuning

Stepper motor driven plunges are installed in two of the 7 cavity cells for tuning. The pick-up signal phase of the cavity's centre cell is compared with the phase of the incident input coupler power. The measured phase difference drives both plungers in parallel in order to keep the phase difference at 0. Thereby the cavity appears as a real load for the incident rf under all operation conditions. Signals of additional pick-up loops in both plunger-cells are used to keep the field distribution symmetric over the 7 cavity cells [1].

Phasing

The rf phases of each rf system related to the beam are controlled by a phasing-automatic. The phasing-automatic calculates the synchronous phase and the phase offset of each rf system and keeps the rf phase difference between the rf systems at 0. The inaccuracy of the phasing-automatic is less than 5°. The experience at HERA shows that phasing rf systems in this way is more convenient and precise than the common method using the synchrotron frequency [3].

3.5.3.4 Summary of Data of the Planned PETRA-III RF System

Transmitter	**Units**	**Nominal Data**	**Data for nominal Beam Operation @ 20MV, 100mA**	**Data for 1-Transmitter Operation @1440kW**
No. of Transmitters	-	2	2	1
Number of Klystrons	-	4	4	2
Klystron Voltage	kV	75	60	73
Klystron Current	A	<18	<13	<17
RF Frequency	MHz	499.67	499.67	499.67
Klystron RF -Output Power	kW	800	398	720
Klystron Efficiency	%	>60	>50	>55

Cavities	**Units**	**Nominal Data**	**Data for nominal Beam Operation @ 20MV, 100mA**	**Data for 1-Transmitter Operation @1440kW**
No. of Cavities	-	12	12	12
Cavity-Type	-	7-cell, copper	7-cell, copper	7-cell, copper
Shunt-Impedance per Cavity	MΩ	23	23	23
Voltage per Cavity	MV	>2.5	1.67	1.67
Overvoltage Factor	-	-	2.6	2.6
Beam Current	mA	-	100	83
Synchronous Phase	degree	-	22.3	22.3
Cavity Detuning	degree		40.4	35.2
Cavity Detuning	kHz		21.3	17.7
Copper Loss per Cavity	kW	>150	60.3	60.3
Coupling Factor	-	-	2.0	2.0
Power per Coupler	kW	200	124	113
Power to Beam per Cavity	kW	-	63.2	52.5

3.5.4 Reliability of RF Systems

The beam-times for users of synchrotron radiation machines are planned long-term in common. Even short breaks of some ten minutes due to technical problems could make experiments worthless. Therefore particular attention must be put on the reliability of all essential accelerator components.

To investigate the reliability rf systems trips and repairs of the 11 rf systems of HERA, DORIS and DESY were used as a data base. 470 events of 4900 transmitter operation-days have been analysed. It turns out that the mean time between two trips (MTBTrip) is about 10.5 days. The reliability of the rf systems at the machines mentioned is amazingly alike although they differ in both the mode of operation and the assigned technology.

An evaluation of the trips of the rf systems at APS in Argonne [4], at ESRF in Grenoble [5] and at LEP in Geneve [6] results in still more amazing results. The mean time between two trips of these systems is between 8 and 12 days (in average also about 10 days).

The reliabilities of the mentioned rf systems are shown in the following table.

Reliabilities of RF Systems

Machine	HERA	DORIS-3	DESY-2	APS [3]	ESRF [4]	LEP [5]
Year of Analysis	1999-2000	2001	2002	2001	2001	1999
Number of rf Systems	8	2	1	2	2	20
Type of rf system	2 Kly., 10…16 Cav.	1 Kly., 4 Cav.	2 Kly., 8 Cav.	1 Kly., 8 Cav.	1 Kly., 2…4 Cav.	2 Kly., 14…16 Cav.
MTBTrip	1,2d	6,5d	11d	6d	4d	0,45d
MTBTrip per rf system	**10d**	**13d**	**11d**	**12d**	**8d**	**9d**

Assumed that the finding is not pure chance the explanation for the amazing uniformity of reliabilities could be as follows:
Rf systems in MW power range contain large quantities of auxiliary devices, sensors and interlock electronics. The individual reliabilities are very different between comparable components of different systems. But the large quantity averages the individual reliabilities to a mean value of about 10 days.
However, this doesn't mean, that building more reliable rf systems is impossible. The investigation of the 470 registered trips of the 11 rf systems at HERA, DORIS and DESY showed that just every 6th to 10th trip has to be a repaired. Mostly pushing the RESET-button was sufficient (=> MTBFailure = 60…100 d). Would it be possible to design a rf system that shut down only in case that some part is really out of order the reliability could be increased by a factor of 6 to 10.
The strategy foreseen for PETRA-III is monitoring all important time-critical signals using two or three independent sensors and/or checking the sensor-signals for plausibility.

Example 1: Klystron Focus Interlock:

Sensors for:
- Current through the solenoid,
- Voltage over the solenoid,
- Magnetic field inside the solenoid

Klystron high voltage is only switched off if at least 2 of the signals will exceed the limit.

Monitoring the large number of non time-critical signals can be made more reliable by computing their time-behaviour.

Example 2: Klystron Body-Temperature Interlock:

- Slow temperature raise above the limit => decrease klystron-current until temperature is stable.
- Fast temperature raise above the limit => switch off klystron high-voltage
- Instantaneous raise above the limit => ignore (must be sensor or electronic error)

In practice it doesn't seem possible to improve the reliability by a factor of 6 or 10 in such a way. But doubling seems to be realistic and is defined as one goal for the new rf systems of PETRA-III.

3.5.5 The RF System for the Longitudinal Feedback

For damping the coupled multi-bunch oscillations in PETRA III a high-performance multi-bunch feedback-system is required. The revolution frequency of PETRA is 130.3 kHz. The bunch repetition rate is 125 MHz with 960 bunches and 8 ns bunch spacing. The bunch repetition rate determines the raster of possible frequency ranges of the longitudinal feedback-system. The device for coupling the feedback rf to the beam defines additional limits for usable feedback frequency bands. For longitudinal feedbacks cavities are common used. To keep the cavities dimensions compact frequencies above 750 MHz are meaningful. The upper frequency limit is given by the cut-off frequency of the vacuum chamber which is about 2 GHz. Optimal feedback frequencies are about 1000 MHz to 1375 MHz. A feedback cavity with optimized high shunt-impedance and low HOM-impedances was developed for DAΦNE [8]. This type of cavity is working at BESSY and ELETTRA e.g. with some modifications. The centre frequencies and bandwidths of these cavities are 1200 MHz / 220 MHz at BESSY and 1375 MHz / 270 MHz at ELETTRA. The shunt-impedances are about 800 Ω.
The cavity bandwidth needed for PETRA-III is: $B = \frac{f_{rev} \cdot n_b}{2} = \frac{130.2 kHz \cdot 960}{2} = 62.5 MHz$.
Therefore the quality factor and thus the shunt impedance could be 4 times higher than that of the DAΦNE feedback cavity. The shunt impedance could be increased to 3 kΩ for our application.
For PETRA III a feedback voltage of approx. 12 kV is required. The installation of 8 modified feedback cavities of the DAΦNE-Type with 3 kΩ shunt-impedance each is foreseen. The required feedback rf power would be 3 kW. For generating the rf power solid state amplifiers are suitable. The assembly foreseen at present is connecting 2 feedback cavities to one 1 kW amplifier. The costs of the feedback rf system are estimated to 1.5 M€. The costs of the solid-state amplifiers are already about 1 M€. Therefore an alternative solution using TWT-amplifiers is under consideration.

3.5.6 Upgrade to 200 mA Beam Current

It is foreseen to increase the maximum beam current of PETRA-III to 200 mA in a later upgrade. The installed 7-cell cavities are probably not suitable for these currents because of their HOM-impedances and should therefore be replaced. Superconducting or normal conducting
1-cell cavities with HOM-optimised design and additional HOM-damping are possible solutions. Both solutions are considered in the following.

3.5.6.1 Consideration of 1-Cell, Normal Conducting Cavities

The maximum power loss on a water cooled copper surface is about 100 W/cm². At higher power levels a vapour layer decreases the cooling efficiency. Therefore the maximum power loss of a normal conducting 1-cell cavity at 500 MHz is limited to 300…400 kW. Assuming a shunt impedance of 3 MΩ the maximum possible cavity voltage can be 1.3 … 1.5 MV. Actually values are much lower because of the restricted cooling possibilities due to plunger beam pipe and coupler flanges. Cavity voltages of 800 kV for a 500-MHz cavity (SPring8) or 850 kV for a 470-MHz cavity (PEP-2) are state of the art. For generating the required 20 MV at least 25 cavities of such type would be necessary. The required rf power for 200 mA beam current would be

$$P_{Cav-Loss} + P_{HOM} + P_{Beam} = 25 \cdot \frac{800kV^2}{2 \cdot 3M\Omega} + 100kW + 1318kW = 4.09MW \quad \text{in that case}$$

For calculating the nominal rf power required to be installed additional 5% transmission losses and 20% safety margin must be taken into account. The installed rf power has to be at least 5.1 MW.

In order to use further on 800-kW klystrons it would be practical to install a 3rd 1.6-MW transmitter for this upgrading option. The available rf power would be 4.8 MW in that case. Because of the slightly less available rf power the number of rf cavities must be accordingly increased. Furthermore the total number of the cavities has to be divisible by 3 for getting equal rf systems. Last but not least beam operation at 20 MV with >100 mA beam current must be possible by having only 2 of 3 transmitters in service in order to have a certain redundancy.

The installation of 15 1-cell cavities per rf system would meet this requirements. In case that 1 of the 3 rf systems is out of order beam operation at 100 mA would still be possible. In normal operation (3 rf systems with 45 cavities, 20 MV circumference voltage, 200 mA beam current) the power per cavity-coupler would be quite moderate. The coupler power would be:

$$P_{Cav-Loss} + P_{HOM} + P_{Beam} = \frac{444kV^2}{2 \cdot 3M\Omega} + \frac{100kW}{45} + \frac{1318kW}{45} = 64kW\ .$$

The rf systems would operate at 63% of their nominal power at nominal beam conditions.

3.5.6.2 Consideration of 1-Cell, Superconducting Cavities

Superconducting cavities (s.c.) exhibit several advantages compared to normal conducting cavities (n.c.). Because of their negligible surface resistivity the dissipated power in the structures is low and higher accelerating voltages can be realised very easily. This gives the possibility to optimise the cavity shape in order to minimize their Higher Order Mode (HOM) impedance. Additionally HOM damping at s.c. cavities is easier compared to n.c. cavities. Both the smaller number of requires cavities and their better damped HOMs lead to increased thresholds for beam instabilities. For the DIAMOND project the usability of s.c. cavities in synchrotron-light sources were considered [7]. For PETRA-III the rf systems have to be designed for a beam power of about 1.4 MW @200mA (HOM power included). Plus 5% transmission losses and 20% safety margin gives 1.75 MW required rf power. Thus the installed nominal klystron power of 3.2 MW is more than sufficient. Supposing a voltage of 2 MV per cavity (6,7 MV/m) the installation of 10 superconducting cavities are required for PETRA-III. The resulting coupler power of 142 kW per cavity would be moderate.

3.5.6.3 Superconducting versus Normal Conducting 1-Cell Cavities

	Units	n.c. Cavities	s.c. Cavities
number of transmitters	-	3	2
nominal rf power per transmitter	MW	1.6	1.6
rf power per transmitter @200mA	MW	1.02	0.75
total rf power @200mA	MW	3.07	1.49
number of cavities per rf system	-	15	5
total number of cavities	-	45	10
voltage per cavity	MV	0.444	2.0
gradient	MV/m	1,5	6,7
power per coupler @200mA	kW	64	142
power to beam per cavity @200mA	kW	32	142

Using s.c. cavities for the upgrade of PETRA-III would be quite attractive, especially considering the energy consumption. The AC input power for two s.c. rf systems is about 3 MW lower compared to three n.c. rf systems. The investment costs are estimated to at least 10 M€ for both options.
However, s.c. cavities require much more complex interlock systems compared to n.c. cavities. Therefore one can assume that they fail more frequently. The experience at HERA show a trip rate of about 70 days for a s.c. cavity (compared to 300 days for a n.c. cavity). At LEP the trip rate was about 23 days for a single s.c. cavity. At CESR and KEK-B the experience is similar [7]. Partially the lower reliability of s.c. cavities is compensated by the lower number of required cavities. About the expected reliability of a s.c. PETRA-III rf system one can just speculate. But for 10 s.c. cavities 1…3 trips per week can be expected. The desired doubling of the over-all reliability of the PETRA rf systems from MTBTrip = 5d at present to MTBTrip > 10d could become more difficult by using s.c. instead of n.c. cavities. It is hoped that in some years when the decision for an upgrade has to be made sufficient experience about reliability is available from light sources under construction at present.

3.5.7 Conclusion

Reusing essential parts of the present PETRA-II rf system is planned because of cost, schedule and manpower reasons. Only renewing the klystron hv-supplies, crowbar-systems, klystron-modulators, interlock electronics and control-system is foreseen to ensure a more reliable operation and efficient diagnostics. To be able to store 100 mA beam current at 8 ns bunch-spacing the shunt-impedance of the 500-MHz cavities will be decreased by removing 4 of the 16 installed 7-cell-cavities. Additionally installing a broadband longitudinal multi-bunch feedback system is foreseen (see chapter **9 Multi-Bunch Feedback System**).

For a future upgrade of PETRA III to 200 mA beam current the existing 7-cell-cavities will be replaced by HOM-optimized 1-cell cavities. The decision whether superconducting or normal conducting cavities are more suitable for PETRA-III has been made yet.

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