BEAM CURRENT LIMITATIONS IN THE SYNCHROTRON LIGHT SOURCE PETRA III

K. Balewski, R. Wanzenberg , DESY, Hamburg, Germany

Abstract

At DESY it is planned to convert the PETRA ring into a synchrotron radiation facility, called PETRA III, in 2007. Different operation modes with single bunch intensities of up-to 2.5 mA have been considered to serve the needs of the user communities. A first estimate of the impedance budget of PETRA III is given based on analytical models and numerical wakefield calculations of several vacuum chamber elements. The impedance model includes higher order modes (HOMs) of the cavities to cover multi bunch aspects. The beam current limitations due to multi and single bunch instabilities are discussed. The build up of an electron cloud is also investigated for the option of using a positron beam to generate the synchrotron radiation.

INTRODUCTION

The PETRA ring was built in 1976 as an electron - positron collider and was operated from 1978 to 1986 in this collider mode. Since 1988 PETRA is used as a preaccelerator for the HERA lepton hadron collider ring at DESY. It is planned to convert the PETRA ring into a dedicated 3rd generation synchrotron radiation facility [1,2], called PETRA III, after the end of the present HERA collider physics program in 2007. One octant of the PETRA ring will be completely redesigned to provide space for 13 insertion devices. The planned location for the new hall is shown in Fig. 1.

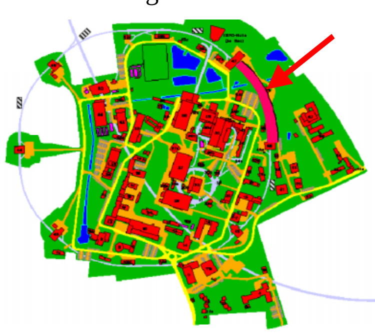

Figure 1: Ground Plan of the DESY site with the PETRA ring. The new experimental hall (red) is situated between the PETRA halls North-East and East.

The planned facility aims for a very high brilliance of about 10^{21} photons /sec /0,1%BW /mm^2/ mrad^2 using a low emittance (1 nm rad) positron beam with an energy of 6 GeV. The standard bunch filling pattern will consist of a large number of equally spaced bunches with a low bunch population. Additionally a special operation mode is required for time-resolved experiments with higher bunch charges (2.5 mA per bunch) in 40 equally spaced bunches. The main parameters of PETRA III are summarised in Tab. 1.

A beam circulating in a storage ring interacts with its vacuum chamber surroundings via electromagnetic fields. These wake fields [3] in turn act back on the beam and can lead to instabilities, which limit either the achievable current per bunch or the total current or even both. The total impedance of PETRA III depends on the RF cavities, bellows, beam position monitors, kickers, undulator chambers, pump ports, flanges and many other objects. For several objects the wake potential is known in detail from numerical calculations [4]. But since a detailed knowledge of the impedance all vacuum chamber components is presently not available the instability thresholds have also been estimated from the experience with the existing machine PETRA II.

Table 1: PETRA III parameters

Parameter	PETRA III	
Energy / GeV	6	
Circumference /m	2304	
RF Frequency / MHz	500	
RF harmonic number	3840	
RF Voltage / MV	20	
Momentum compaction	1.22×10^{-3}	
Synchrotron tune	0.049	
Total current / mA	100	
Number of bunches	960	40
Bunch population / 10^{10}	0.25	12
Bunch separation / ns	8	192
Emittance (horz. / vert.) /nm	1 / 0.01	
Bunch length / mm	12	
Damping time H/V/L / ms	16 / 16 / 8	

IMPEDANCE

Nearly the entire vacuum system of the existing storage ring PETRA will be replaced during the conversion to a synchrotron radiation facility. Several undulator chambers with a small vertical gap of about 7 mm are planned to be installed in the so called "new" octant between the halls North-East and East. The vacuum chamber in the seven old octants will have a vertical height of 40 mm and a total width of 80 mm. The cross section of a prototype design of the vacuum chamber is shown in Fig. 2. The slit between the beam chamber and the ante-chamber extends over the whole length of 5.4 m of the chamber. This will reduce the impedance of the vacuum chamber compared to the presently installed chamber with several about 5 cm

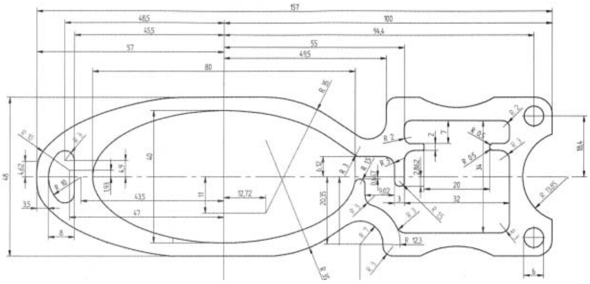

Figure 2: Cross section of a prototype design of the dipole vacuum chamber in the seven "old" octants. An ante-chamber housed the NEG pump.

long pumping slits. Furthermore only 12 seven cell cavities of the presently 16 installed cavities are needed for PETRA III. On the other hand the undulator chambers in the "new" octant will have several tapered transitions between vacuum chambers with standard cross sections and undulator chambers with small cross sections. A first estimate of the impedance of PETRA III includes the following objects:

- 12 seven-cell cavities
- 196 dipole vacuum chambers in the seven old octants.
- 13 small gap (7mm) undulator chambers in the new octant.

Detailed numerical calculation of the wake fields have been done for the seven-cell cavities and the dipole vacuum chambers, using the MAFIA code [4]. Fig. 4 shows the electric wake field of a bunch, which transverses the seven-cell PETRA cavity on axis. The impedance of the undulator chambers has been estimated based on an analytical model for a discontinuity in the beam pipe [5,6], which is certainly a pessimistic model for the undulator chambers. We will express the impedance in terms of the so-called loss and kick parameters, which are defined via the wake potential and the normalised beam line charge density. The loss parameter $k_{\|}(n)$ and the kick parameter $k_{\perp}(n)$ are defined as:

$$k_{\|}(n) = \int ds \;\; W_{\|}(s) \frac{d^n}{ds^n} \lambda(s), \quad k_{\perp}(n) = \int ds \;\; W_{\perp}(s) \frac{d^n}{ds^n} \lambda(s) \, ,$$

where $\lambda(s)$ is the line charge density, $W_{\|}(s)$ the longitudinal and $W_{\perp}(s)$ the transverse wake potential. The total energy loss of the beam is $q^2 \; k_{\|}(0)$. Based on previous measurements and calculations [7,8] the total impedance of the existing machine PETRA II has been estimated in [1]. The results are summarised in Table 2.

Table 2: loss and kick parameters for PETRA II

Parameter	PETRA II (total)
$k_{\|}(0)$ (V/pC)	-128
$k_{\|}(1)$ (V/ pC m)	-2900
$k_{\perp}(1)$ (V/ pC m)	1500

The contributions to the impedance of PETRA III from the 12 cavities, 196 dipole vacuum chambers and 13 small gap vacuum chambers in the insertion devices are summarised in Table 3 for a bunch length of 1 cm (rms).

Table 3: loss and kick parameters for PETRA III

Parameter	Cavities	Dipole chambers	Small gap chambers
$k_{\|}(0)$ (V/pC)	-44	-4.8×10^{-5}	-23
$k_{\|}(1)$ (V/ pC m)	-1600	-0.1	-180
$k_{\perp}(1)$ (V/ pC m)	370	-7.6×10^{-5}	2900

This first estimates indicate that the transverse impdance of PETRA III will be about a factor of two larger than the impedance of PETRA II.

The long range wake field is dominated by higher order modes (HOMs) in the cavities. The effective shunt impedance has been measured at PETRA II [1]. The results are summarised in Table 4.

Table 4: Measured effective multibunch impedance .

Parameter	PETRA II (total)
$Z_{\|eff}$ (MΩ)	3.6
$Z_{\perp\,eff}$ (MΩ/m)	50

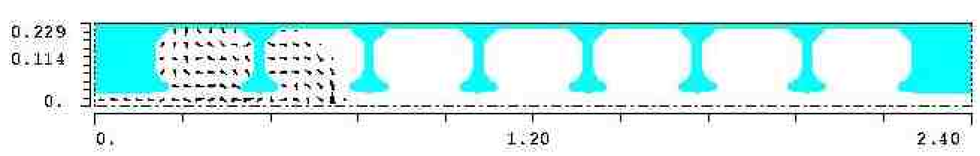

Figure 4: Electric wake field in PETRA 7-cell cavity. A bunch transverses the cavity on axis.

INSTABILITIES

Single bunch instabilities

A transverse instability has been observed in PETRA when the storage ring was operated in the collider mode [9]. Presently single bunch currents of 10 mA can be stored in PETRA II without any evidence for a transverse or longitudinal instability. The instability threshold for mode coupling instabilities can be estimated from the tune shifts of the lowest order modes in the longitudinal and transverse planes [1,10]:

$$\Delta Q_s = Q_s \frac{I_B\, R\, T_0}{2 h V_{rf}} k_{\|}(1), \quad \Delta Q_\beta = \frac{I_B \langle\beta\rangle\, T_0}{4\pi\, E/e} k_{\perp}(0),$$

where I_B is the single bunch current, R = 367 m is the mean machine radius and $\langle\beta\rangle = 20$ m is the average β–function. We obtain $|\Delta Q_s/Qs| = 0.083$ and $|\Delta Q_\beta/Q_s| = 0.34$ using the estimates for $k_{\|}(1)$ and $k_{\perp}(1)$ for PETRA III. The transverse effect of the impedance of the small gap chamber has been overestimated since these chambers are located in a section with a small β–function. If one assumes an average β–function of 10 m for the small gap chambers one obtains a tune shift of only $|\Delta Q_\beta/Q_s| = 0.2$. For these small relative tune shifts one expects no mode coupling instabilities for the design bunch current of 2.5 mA. This result is in agreement with the experience at other light sources with small gap chambers [11,12].

Coupled bunch instabilities

The growth rates for longitudinal and transverse coupled bunch instabilities can be estimated from the measured effective impedance of PETRA II according to:

$$\frac{1}{\tau_{\|}} = \frac{2\pi Q_S}{T_0} \frac{I_{tot} Z_{\|eff}}{2\, V_{rf}}, \quad \frac{1}{\tau_{\perp}} = \frac{2\pi}{T_0} \frac{I_{tot} \beta_{cav} Z_{\perp eff}}{4\pi\, E/e}.$$

The longitudinal growth rate of 360 Hz and the transverse growth rate of about 1100 Hz is significantly larger than the radiation damping rates of 125 Hz (longitudinal) and 62.5 Hz (transverse). Therefore a powerful feedback system is required to provide additional damping.

Electron cloud effects

It is one option to operate PETRA III with positrons instead of electrons. In positron storage rings electrons produced by photoemission and secondary emission may accumulate in the vacuum chamber forming an “electron cloud”. Electron cloud effects have not been observed in PETRA II. Single bunch intabilities due to electron clouds are also not expected for PETRA III according to simulation results [13].

CONCLUSION

The impedance of the planned X-ray light source PETRA III has been estimated based on measurements for the existing storage ring PETRA II, numerical calculations and analytical results for a discontinuity in the beam pipe. Small gap chambers in the insertion devices will contribute significantly to the transverse impedance of PETRA III. But we expect no mode coupling instabilities for the operation mode with 40 bunches which requires a single bunch current of 2.5 mA since tune shifts in units of the synchrotron tune are small. Multi-bunch instabilities are mainly driven by parasitic modes in the RF cavities. The effective impedance has been determined from measurements at PETRA II. The expected growth rate of coupled bunch instabilities in PETRA III is much larger than the radiation damping rate. Therefore a powerful longitudinal and transverse multi-bunch feedback is required to provide the additional damping.

REFERENCES

[1] PETRA III: A low Emittance Synchrotron Radiation Source”, Technical Design Report, DESY 2004-035

[2] K. Balewski et al., “PETRA III: A New High Brilliance Synchrotron Radiation Source at DESY“, This conference

[3] T. Weiland, R. Wanzenberg: “Wakefields and Impedances”, in M. Dienes, M. Month, S. Turner (Eds.) Proceedings US-CERN School, Hilton Head 1990, Springer-Verlag, Berlin , 1992

[4] T. Weiland, “On the Numerical Solution of Maxwell’s Equations and Applications in the Field of Accelerator Physics”, Part. Acc. 15 (1984)

[5] L. Palumbo, “Analytical Calculation of the Impedance of a Discontinuity”, Part. Acc. 25 (1990)

[6] E. Gianfelice, L. Palumbo, “Dipole Impedance of a Conducting Cylindrical Pipe with a Discontinuous Cross Section”, IEEE Trans. NS, Vol 37 (1990)

[7] T. Weiland, “PETRA’s impedance “, Internal report M-81/04

[8] R. Klatt, R.D. Kohaupt, T. Weiland, “Theoretical Prediction of Head tail Tune shift in PETRA”, IEEE Trans. NS, Vol 32, pp.2356-2358 (1985)

[9] R. D. Kohaupt, “Transverse instability in PETRA”, Proc. 11th Int. Conf. in High Energy Acc., CERN (1980) EXS Vol. 40, Birkhauser Verlag, p. 566

[10] K. Balewski, “Analyse der transversalen Moden-Kopplungsinstabilitaet fuer lokalisierte HF-Strukturen und ihre Kompensierbarkeit durch Rueckkopplungssystemen, DESY 89-108, Aug. 1989

[11] T. F. Günzel “Evaluation of the Vertical Transverse Impedance of the ESRF-Machine by Element-wise Wakefield Calculation“, Proc. of EPAC 2002, Paris, France

[12] K. Harkay et al. “A Preliminary Comparison of Beam Instabilities among ESRF, APS and SPRING-8 X-ray Storage Ring Light Sources “, Proc. of EPAC 2002, Paris, France

[13] R. Wanzenberg: “Simulation of Electron Cloud Effects in the PETRA Positron Storage Ring”, Internal report, DESY M 03-02, Dec. 2003