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MOPD079.
19. T. Mitsuhashi, Spatial coherency of the synchrotron radiation at the visible light region and its application for the electron beam profile measurement, in Proceedings of PAC97, p. 766-768, Vancouver, Canada, May, 1997.
20. T. Mitsuhashi and T. Naito, in Proceedings of EPAC98, p. 1565, Stockholm, Sweden, June, 1998.
21. N. Takeuchi, T. Mitsuhashi, M. Itoh, T. Yatagai, Wavefront Distortion Measurement of a SR Extraction Mirror for the Beam Profile Monitor Using Shack-Hartmann Method, in Proceedings of PAC 1997, p. 859, Vancouver, Canada, May, 1997.
22. T. Mitsuhashi and M. Tadano, in Proceedings of APAC 2001, p. 704, Beijing, China, 2001.
23. M. J. Boland, T. Mitsuhashi and K. P. Wootton, Low Noise and High Dynamic Range Optical Interferometer Beam Size Measurements, presented at the International Beam Instrumentation Conference 2013, Oxford, UK, September, 2013, TUPF20.
24. T. Naito and T. Mitsuhashi, Physical Review Special Topics - Accelerators and Beams **9** (12), 122802 (2006).
25. M. J. Boland, T. Mitsuhashi, T. Naito and K. P. Wootton, Intensity Imbalance Optical Interferometer Beam Size Monitor, in Proceedings of International Beam Instrumentation Conference 2012, Tsukuba, Japan, October, 2012, WECC03.
26. A. Franchi and L. Farvacque, ICFA Beam Dynamics Newsletter 57, pp. 105-118 (2007).
27. K. Ohmi, K. Hirata and K. Oide, Phys. Rev. E, **49** (1), 751 (1994).
28. A. Terebilo, Proceedings of PAC01, p. 3203, Chicago, Illinois, USA (2001).
29. B. C. Cowie, A. Tadich, and L. Thomsen, AIP Conf. Proc., **1234**, 307 (2010).
30. K. P. Wootton, R. P. Rassool, M. J. Boland and B. C. C. Cowie, APPLE-II Undulator Magnetic Fields Characterised from Undulator Radiation, in Proceedings of International Beam Instrumentation Conference 2013, Oxford, UK, September, 2013, TUPF19.
31. T. Tanaka and H. Kitamura, J. Synch. Rad. **8**, 1221 (2001).

3.4 Beam Dynamics Activities at PETRA III

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3.4.1 Introduction

PETRA III [1] is a third generation synchrotron radiation facility at DESY. The PETRA ring was originally built as an electron and positron collider in 1976. From 1988 until 2007 PETRA was used as a pre-accelerator for the HERA lepton hadron collider ring. During the conversion to a synchrotron radiation facility from 2007 to 2009 one octant of the PETRA ring has been completely redesigned to provide space for 14 undulators. The commissioning with beam started in April 2009 and user runs have been started in 2010 [2]. Until the end of 2012 PETRA III was running in a top-up operation mode with positrons since PETRA III was sharing the same pre-accelerator chain with the synchrotron light source DORIS, which was running with positrons to avoid problems with ionized dust particles. The main design parameters are listed in Table 1.

Table 1: PETRA III design parameters

Parameter		*PETRA III*	
Energy	GeV	6	
Circumference	m	2304	
Total current	mA	100	
Number of bunches		960	40
Bunch population	10^{10}	0.5	12
Bunch separation	ns	8	192
Emittance (horz. / vert.)	nm	1 / 0.01	

The design current of 100 mA has been achieved but using different filling schemes than originally foreseen, since a vertical emittance blow-up has been observed for a filling scheme with 960 equidistantly spaced positron bunches. In 2010 studies with different filling schemes indicated already that the vertical emittance blow-up is related to an Electron Cloud (EC) instability [3].

In 2011 three filling schemes, with bunch to bunch spacing of 192 ns (40 bunches), 128 ns (60 bunches) and 32 ns (240 bunches) have been used. For a filling scheme with 40 and 60 bunches no phenomena were observed which could be related to EC effects. However, for the filling scheme with 240 bunches (32 ns spacing) a slight vertical emittance growth was observed (ε_y~0.025 nm), which was still acceptable for user operation. During the start-up phase for the 2012 running period scrubbing runs with 480 equidistant bunches and a total beam current of 100 mA have been done for 4 days. During the scrubbing run, phenomena related to EC effects have been observed: horizontal and vertical emittance growth and extra lines in the vertical tune spectra. After the scrubbing run it was possible to operate PETRA III with 240 bunches with a smaller vertical emittance (ε_y~0.01 nm) than in 2011. It was also possible to run with 320 equidistantly spaced bunches and a small vertical emittance growth. But for filling schemes with 480 bunches and 960 bunches (8 ns bunch spacing, design parameter) a significant emittance growth has been observed, which excludes these filling schemes for user runs. The present understanding of the EC effects at PETRA III is summarized in Refs. [4, 5].

Since January 2013 PETRA III is running with electrons. It is now possible to operate the storage ring with 960 bunches (8 ns bunch spacing) without any vertical emittance growth. But the filling schemes with fewer bunches, which were successfully used during positron operation, suffer from ion effects. Some details are reported in the next section.

Further beam dynamics activities at PETRA III concentrated on the understanding of the beam dynamics of very low emittance beams (160 pm rad) at 3 GeV and the investigation of beam losses during user runs at 6 GeV.

3.4.2 Investigation of Ion Effects

At PETRA III it is now possible to compare the measurement with positron and electron beams for several filling schemes. For some filling schemes a vertical emittance growth was observed in 2013 with an electron beam while this effect was not observed during positron operation. This strongly indicates that the emittance growth is due to ion effects. Classical ion trapping and the fast ion instability were studied via computer simulations in Ref. [6] for PETRA III. However, the measurements indicate that a different ion effect seems to cause the emittance growth, which was first reported from the TRISTAN accumulator ring [7] using a theory of a two beam instability [8]. The transverse motion of the ions, which are produced and trapped by the stored electron beam, and the betatron motion of the beam are coupled. The transverse oscillation of the ions is ~ exp(i Ω t) while the beam oscillates ~ exp(i (m θ - Ω t)), where m is the transverse mode number and θ is the azimuthal coordinate along the storage ring. The frequency Ω is the solution of the fourth order mode equation [7, 8]:

$$(\Omega^2 - \omega_i^{\ 2})\left((\Omega - m\ \omega_0)^2 - \nu_y^{\ 2}\omega_0^{\ 2} - \omega_e^{\ 2}\right) = \omega_e^{\ 2}\omega_i^{\ 2}, \tag{1}$$

where ω_i is the oscillation frequency of the ions in the beam potential and ω_e is the oscillation frequency of the electrons of the beam in the potential of the ions, while ω_0 is revolution frequency and ν_y is the vertical betatron tune.

For the measurement of the vertical emittance an interferometric vertical beam size measurement [9, 10] is used. Synchrotron light from a bending magnet is sent through a double slit and generates an interference pattern. The beam size is calculated from the visibility of the interferogram, which indicates the degree of spatial coherence of the photons. Furthermore, the spectrum of the multibunch oscillations and the tune spectrum of individual bunches are measured using the signals from the feedback system [11].

During studies the filling schemes, which are shown in Fig. 1, were used in 2013. There are 960 nominal positions in PETRA III with spacing of 8 ns, which is presently the smallest possible bunch-to-bunch distance determined by the bandwidth of the multibunch feedback system (the harmonic number is 3840 = 4 x 960). The first four filling schemes (40, 60, 480 and 960 bunches) do not suffer from any vertical emittance growth at a total current of 100 mA and were used for user runs. All the other filling schemes showed a significant vertical emittance growth at a threshold current of about 60 mA. The filling scheme with 240 bunches was used during positron operation without any significant emittance growth in 2012 for user runs.

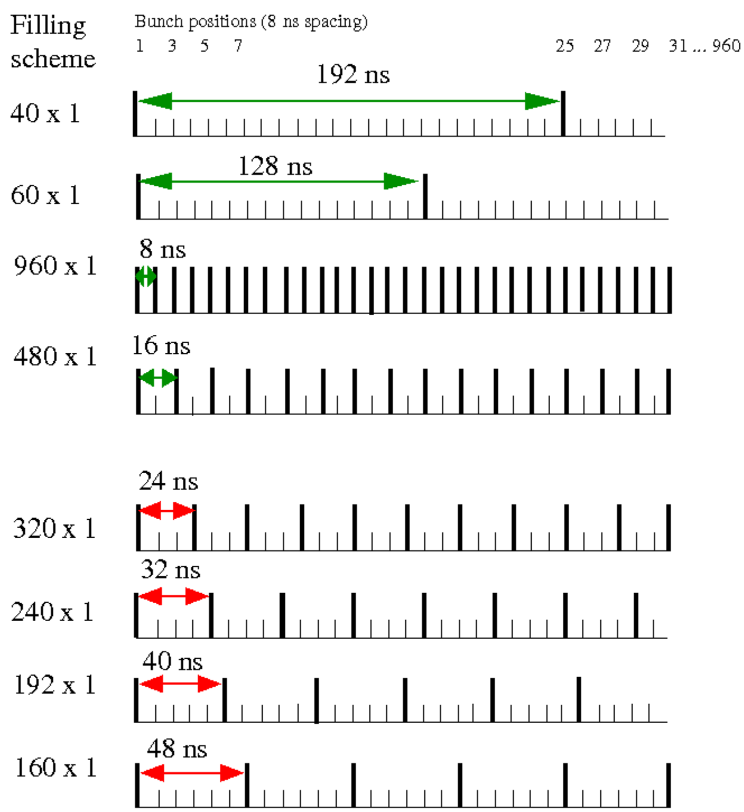

Figure 1: Different bunch filling schemes of PETRA III.

For the filling scheme with 240 bunches a multibunch mode with mode number m=71 corresponding to a frequency of about 9.2 MHz was measured in the multibunch spectrum during studies in March 2013. Eqn. (1) has only a complex solution for mode number m=71 if one assumes an rms beam size of 800 μm (horz.) / 10 μm (vert.) and an ion density of about 20 ions/cm. The solutions of Eqn. (1) for all other mode numbers have four real solutions (no instability). The imaginary part of the complex solution corresponds to the inverse of the growth rate of the two beam instability, which is larger than the damping rate of the multibunch feedback system. These preliminary results indicate that the observations at PETRA III are in agreement with a two beam instability due to ions using the same theory as in Ref. [7, 8].

3.4.3 **Very Low Emittance Beams at 3 GeV**

The interest in realizing a next generation, storage ring based, diffraction limited light source, a so called "ultimate" storage ring (USR), is growing [12]. The design of these machines, which have electron emittances of < ~100 pm in both transverse planes, requires R&D in various accelerator physics and engineering areas before such machines can actually be implemented. Especially collective effects could limit the achievable emittances in an USR.

To contribute to the R&D for an ultimate storage ring PETRA III was operated at an energy of 3 GeV for the first time during a study period in July 2013. It was possible to achieve a horizontal emittance of 160 pm rad which seems to be a new world record with respect to smallest achieved beam emittance in storage rings. An interferometric horizontal beam size measurement [9, 10] was used to measure the emittance. The interferogram is shown in Fig. 2 for a total beam current of 5 mA in 480 bunches or a single bunch current of 10.4 μA. The measured value of 160 pm rad is in agreement with predictions. For higher bunch currents a significant emittance blow-up was observed. The measured emittance versus the single bunch current is shown in Fig. 3.

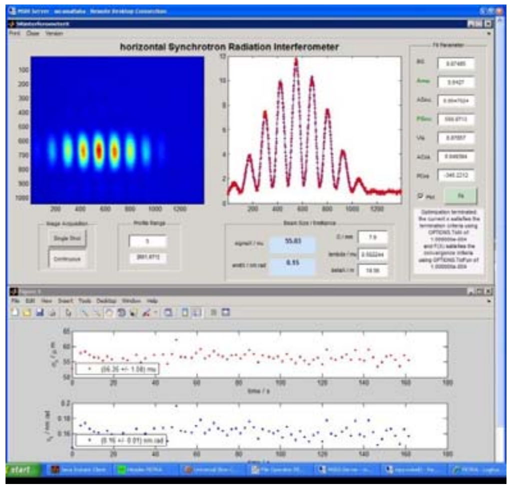

Figure 2: Measured horizontal emittance of 160 pm (calculated from the visibility of the interferogram) for a total beam current of 5 mA in 480 bunches at 3 GeV.

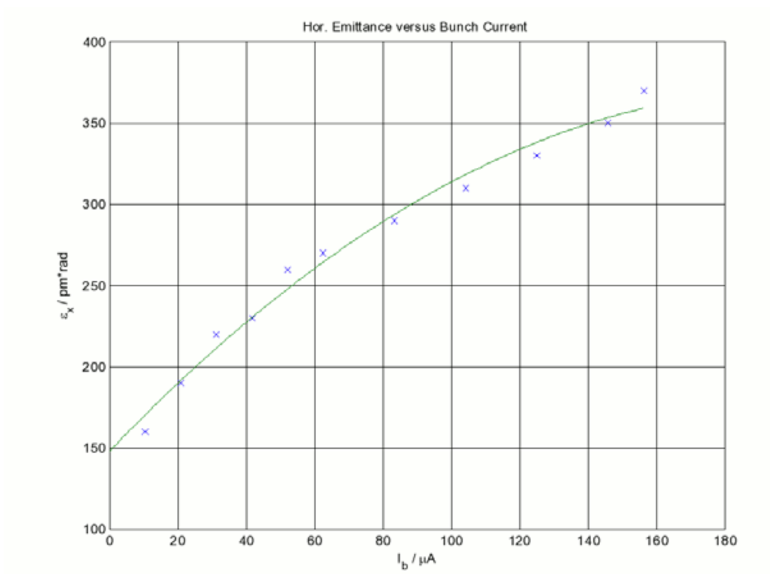

Figure 3: Horizontal emittance versus the single bunch current of PETRA III at 3 GeV.

The emittance increase can be associated with intra-beam scattering (IBS) [13], which leads to an increase of the beam dimensions in all three directions due to multiple Coulomb scattering within the beam. Whether the observed emittance increase is completely in agreement with IBS-theory could not be comprehended from the data taken in July 2013 since only the horizontal beam size was measured. The vertical emittance depends on the degree of coupling compensation and dispersion correction.

Recent measurements in October 2013 indicate that the vertical emittance is for all considered single bunch currents of Fig. 3 smaller than 10 pm rad. Further investigations are necessary to model the measured beam size data in detail.

3.4.4 Beam Losses and Radiation Damage at the Insertion Devices

Radiation damage of machine hardware, electronics and magnet structures has been observed for some time in PETRA III. First signs of radiation damage were observed in the wiggler sections. Performance losses have been observed at several beamlines. The gaps operated at some beamlines have to be decreased or tapers introduced over time and distortions of higher harmonics have been measured. Similar signs of performance loss due to radiation damage have been observed and thoroughly investigated in, e.g., [14, 15].

In situ measurements of the longitudinal peak field profile of all insertion devices (IDs) revealed a partial demagnetization of certain undulators, see Fig. 4.

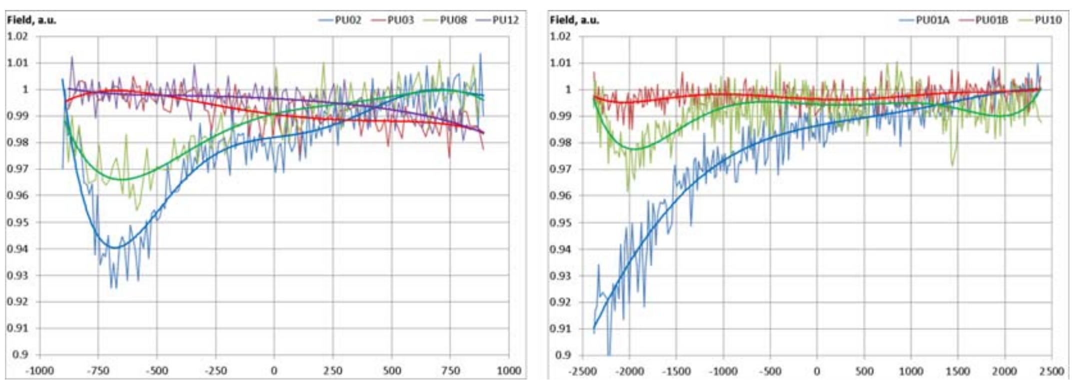

Figure 4: Recent in situ measurements of the longitudinal peak field profile of undulators affected by radiation damage. The lhs shows data for selected 2m IDs. PU02 and PU08 are located upstream in canted straights while PU03 and PU12 are located downstream. On the rhs data for 5m IDs are depicted. All data are normalized to values measured in the laboratory.

In PETRA III 5m long IDs are installed in long straight sections while 2m long undulators are installed in canted straight sections. At the beginning of the experimental hall two 5m IDs, PU01A and PU01B, are installed in the same straight to serve beamline P01. Demagnetization is observed either at the upstream or the downstream end of the IDs but in all cases at positions where the normalized vertical aperture becomes small. The normalized vertical aperture around the ring is shown in Fig. 5.

Together with the fact that at PU01A/B the upstream dipole is located 40m away from the undulator a damage due to synchrotron radiation emitted by dipoles located upstream of the IDs seems to be ruled out. In order to investigate particle losses at the IDs PIN-diode beam loss monitors (BLMs) formerly used in the HERA-e ring [16] have been installed in all straight sections of the new octant. The BLMs are operated in the so called coincidence mode being primarily sensitive to particle losses while suppressing the synchrotron radiation background.

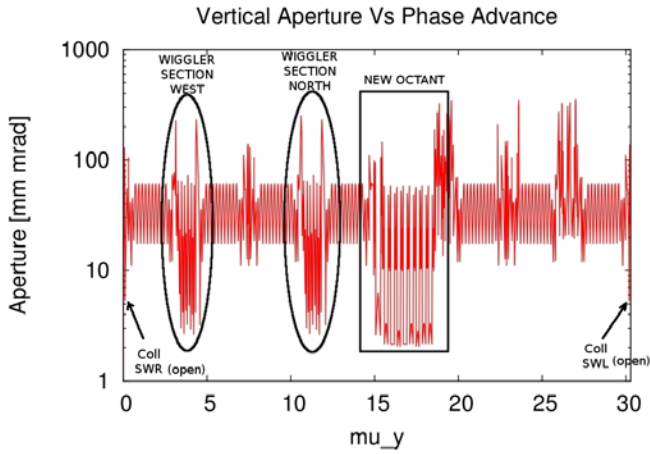

Figure 5: Normalized vertical aperture in PETRA III. Small vertical apertures are set by absorbers in the wiggler sections west and north and by the small gap chambers at the IDs in the new octant. The movable vertical collimators are closed down to ~0.4 mm mrad during user operation.

For global collimation two movable vertical collimators are available in PETRA III. Their main purpose is to intercept injected particles with amplitudes exceeding the available vertical physical aperture. Optimizing the collimator positions reduces the particle losses at injection measured by the PIN beam loss monitors up to a factor of 100, however on the cost of reducing the injection efficiency by ~20%.

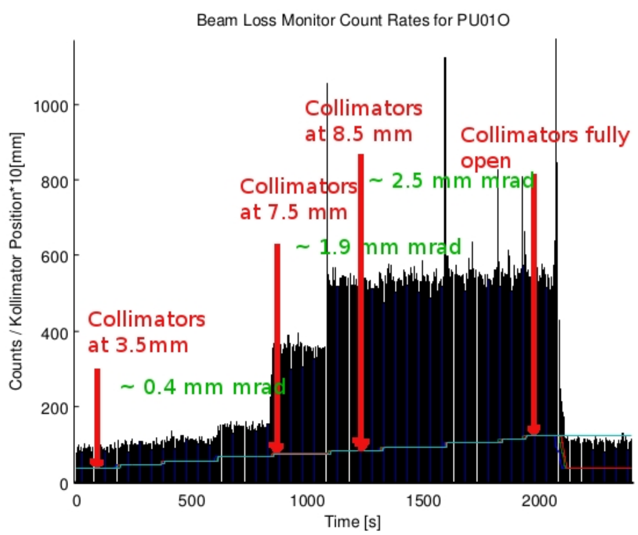

Figure 6: Counts measured at PIN-diode PU01(out) during top up operation with 100mA stored in 960 bunches. The set values of the collimators are varied during the measurement from nominal 3.5 mm (0.4 mm mrad) to fully open corresponding to 12 mm (4.8 mm mrad). The aperture set by the small gap undulator chamber at PU01 corresponds to 2.5 mm mrad.

The collimators are installed in a non dispersive section with large vertical beta-function. The vertical phase advance between them is approximately 75 degree. The efficiency of the collimation system with respect to particle losses occurring from the stored beam has been the subject of dedicated machine studies. During these studies the set points of the collimators have been varied from 3.5 mm (used during user runs) to fully open (12.5mm). In Fig. 6, the counts detected at the PIN-diodes are plotted over time along with the set values of the collimators. The measurement was done with 100mA stored in 960 bunches using top up operation with a 1% variation of the stored current.

While opening the collimators an increase in BLM counts is observed when the normalized aperture set by the collimators becomes comparable to the size of the vertical aperture given by the small gap undulator chambers. Below and above that value the count rates are essentially not affected by the collimator set values indicating the fact that the IDs lie completely inside/outside of the shadow of the collimators. The result for the same experiment performed with 50mA stored in 40 bunches displayed in Fig. 7 shows some remarkable differences.

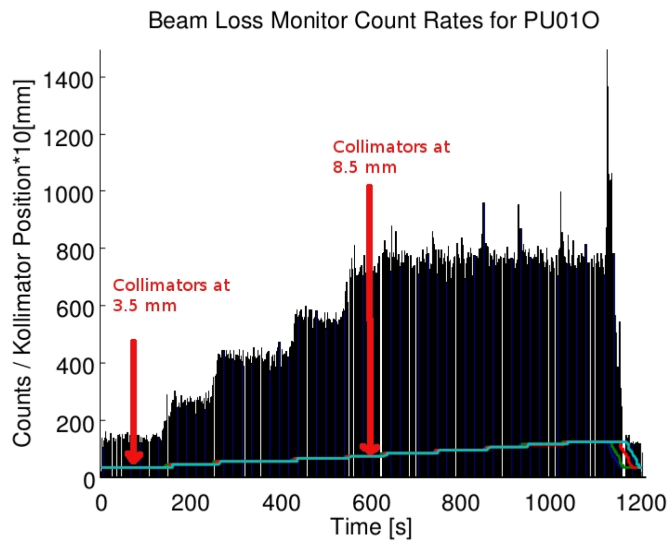

Figure 7: Counts measured at PIN diode PU01(out) during top up operation with 50mA stored in 40 bunches. The set values of the collimators are varied during the measurement from nominal 3.5 mm (0.4 mm mrad) to fully open corresponding to 12 mm (4.8 mm mrad). The aperture set by the small gap undulator chamber at PU01 corresponds to 8.5mm (2.5 mm mrad).

A region of constant count rates at narrow gap values of the collimators is not observed when PETRA III is operated with large single bunch currents. When closing the collimators stepwise the number of counts is gradually reduced without reaching a minimal count rate independent of the aperture limit set by the collimators. The count rate at large single bunch currents is considerably higher reflecting the low beam lifetime dominated by Touschek scattering [17]. Touschek scattered particles are lost due to the large longitudinal momentum deviation resulting from the collision. These scattering events occur all around the ring and scattered particles may be lost within a single turn whereas it can take them several turns to be intercepted by collimators depending on the phase advance and the collimation system. Off momentum beta beating leads to an asymmetry in the aperture limits as seen by particles with large momentum offset. This might provide a route for off momentum particles to escape the collimation system.

More investigations concerning the efficiency of the collimation system are planned in order to improve the understanding and further enhance the protection of the insertion devices. Extensive tracking studies are currently in progress to clarify the observed patterns of particle losses and optimize the placement of additional (local) collimation insertions. An upgrade of the collimation system during the reconstruction phase of the PETRA III extension in 2014 is under consideration.

3.4.5 Acknowledgements

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3.4.6 References

1. PETRA III, Technical Design Report, DESY 2004-035, 2004.
2. K. Balewski, "Comissioning of PETRA III", IPAC'10, Kyoto, Japan, 23-28 May 2010
3. R. Wanzenberg, "Emittance Growth and Tune Spectra at PETRA III", DESY Report, DESY 11-140, 2011.
4. R. Wanzenberg, "Observation of Electron Cloud Phenomena at PETRA III", ECLOUD'12, CERN-2013-002, April 2013.
5. D. R. Grosso et al., "Effect of the surface processing on the secondary electron yield of Al alloy samples", Phys. Rev. ST Accel. Beams 16, 051003 (2013).
6. G. Xia et al., "Ion Effect Issues in PETRA III", PAC09, Vancouver, Canada, (2009)
7. S. Matsumoto et al., "Experimental Study of the Ion Trapping Phenomenon in Tristan-AR", PAC97, Vancouver, Canada, 1997
8. D.G. Koshkarev, P.R. Zenkevich, "Resonance of Coupled Transverse Oscillations in Two Circular Beams", Part. Acc., 1972, Vol 3. pp.1-9
9. T. Naito and T. Mitsuhashi, "Very Small Beam-Size Measurement By a Reflective Synchrotron Radiation Interferometer", Phys. Rev. ST Accel. Beams 9 (2006) 122802.
10. G. Kube, et al. , "Overview of the Diagnostics Systems of PETRA III", EPAC'08, 2008. 23-27 Jun 2008, Genoa, Italy, Conf. Proc. C 0806233 (2008) TUPC111.
11. J. Klute, et al. , "The PETRA III Multibunch Feedback System", DIPAC2011, Hamburg, Germany (2011).
12. Yi Jiao, "Workshop on Accelerator R&D for Ultimate Storage Rings", in ICFA Beam Dynamics Newsletter No. 60 (April 2013, edited by G. Neil).
13. A. Piwinski, "Intra-Beam Scattering", Proc. 9th Int. Conf. on High Energy Acc., Stanford (1974) p 405.
14. M. Borland et al., "Touschek Lifetime and Undulator Damage in the Advanced Photon Source", PAC2005, Knoxville, Tennessee, USA, Conf. Proc. C0505161 (2005) 3835
15. S. Sasaki et al., "Radiation Damage to Advanced Photon Source Undulators", PAC2005, Knoxville, Tennessee, USA, Conf. Proc. C0505161 (2205) 4126
16. K. Wittenburg, "The PIN-diode beam loss monitor system at HERA", DESY HERA Report, DESY-HERA-00-03, 2000
17. A. Piwinski, in Handbook of Accelerator Physics and Engineering, A. Chao and M. Tigner, eds, section 2.5.9 (World Scientific: 1998)