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Author(s) affiliation	ESRF, Grenoble, France DESY, Hamburg, Germany
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Introduction

In fourth generation light sources vertical beam emittance after optics tuning is often well below the diffraction limit. It is then possible to operate the storage rings with increased vertical emittances closer to the diffraction limit, without impact for the X-ray brilliance. The increased vertical beam size allows to increase the Touschek lifetime. Consequently, a more stable storage ring current is obtained, refilling less electrons at each top-up and with less radiation doses in the tunnel. Setting up a system to feedback the vertical emittance to a desired value is thus a strongly desired tool. Beam diagnostics and beam dynamics groups at ESRF-EBS and DESY-PETRA-IV have thus studied a vertical (and potentially horizontal) emittance feedback.

The vertical emittance feedback system is already in place for ESRF-EBS. For PETRA-IV[1] it requires:

- simulations to quantify the conditions for operation of such system (high chromaticity)
- suitable emittance monitors

[1] Schroer, C. G., Agapov, I., Brefeld, W., Brinkmann, R., Chae, Y.-C., Chao, H.-C., Eriksson, M., Keil, J., Nuel GavaldÃ , X., Röhlsberger, R., Seeck, O. H., Sprung, M., Tischer, M., Wanzenberg, R. & Weckert, E. (2018). PETRA IV: the ultralow-emittance source project at DESY. J. Synchrotron Rad. 25, 1277â-1290.

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- Evaluate if strip-line shaker devices are suitable for this application (sufficiently angular kick and frequency range)

The above components have been identified and described in this document.

Simulations of the effect of a white noise signal as blow up for the emittance in EBS[2] and PETRA-IV are performed as a function of chromaticity, showing that the system may work only in presence of chromaticities above 6 units in both planes for EBS and above 3 units in both planes for PETRA-IV.

Measurements to confirm such simulations are performed in ESRF-EBS and detailed in this report.

The use of strip-line shaker devices foreseen for the PETRA-IV Multi Bunch FeedBack (MBFB) system has been evaluated in simulations and allows to control the vertical emittance based on the values provided by the emittance monitors. The system foreseen for PETRA-IV is described in detail.

Vertical emittance feedback for ESRF-EBS

Description of the existing system at ESRF

The general layout of the ESRF-EBS vertical emittance feedback system is represented on Figure 1.

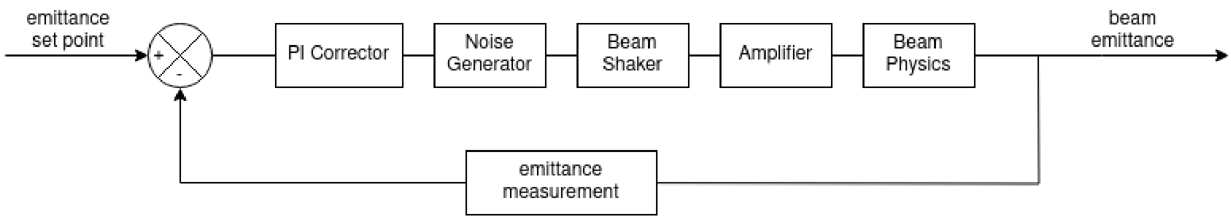

Figure 1: general layout of the ESRF-EBS vertical emittance feedback system

The feedback loop is a digital loop with a period of 2 seconds. This loop is a Python-based Tango device which benefits from all the tango control environment for parameter control, archiving and GUI representation. The corrector used is a simple PI corrector (Proportional-Integral) which ensures that the emittance set-point will eventually be reached.

[2] The Extremely Brilliant Source storage ring of the European Synchrotron Radiation Facility, P. Raimondi *et al., Commun. Phys.* **6**, 82 (2023); https://doi.org/10.1038/s42005-023-01195-z

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The 2-second period has been chosen as a compromise in order to have a feedback loop which can act quickly in case the emittance changes, but slow enough in order to have a clean emittance measurement which has an appropriate signal / noise ratio.

The different parts of the emittance feedback are described below.

Emittance Monitor

The emittance monitors used during standard operation at the ESRF are of the X-ray pinhole type, widely used at synchrotron radiation sources worldwide. Their advantages are robustness, reliability and synchronous assessment of the emittances (beam sizes) in both transversal planes.

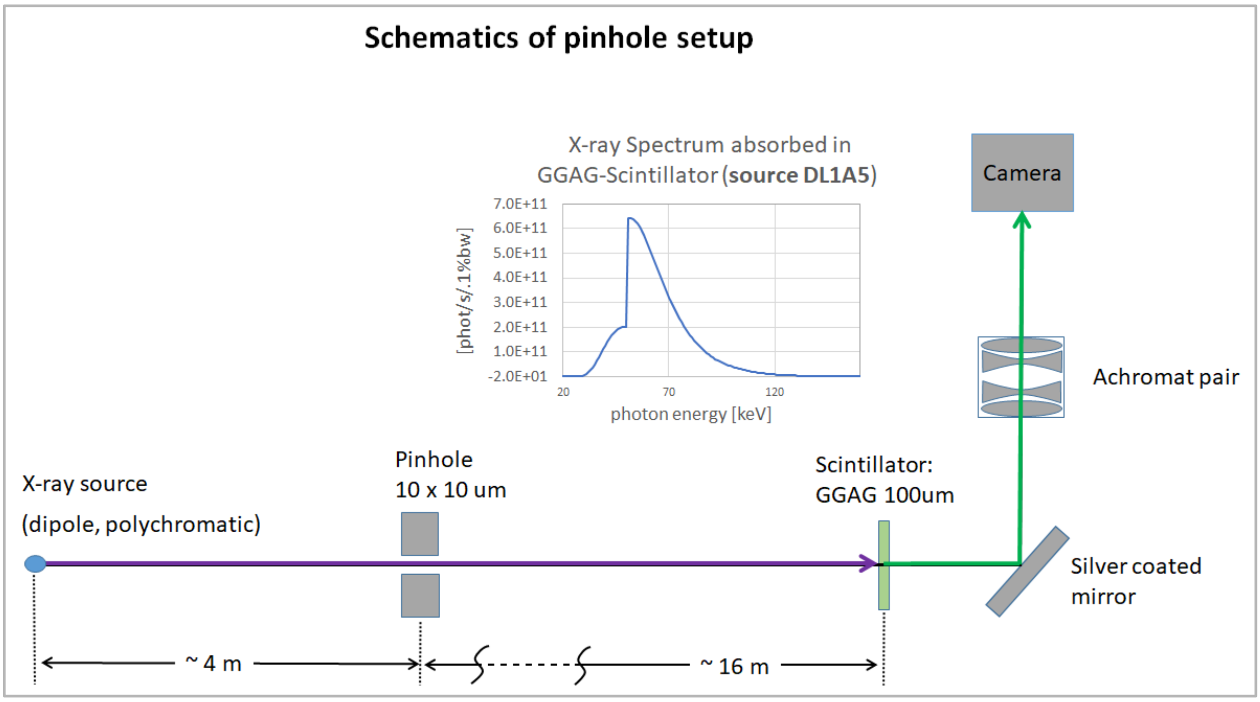

Figure 2: Schematics of pinhole setup.

The ESRF storage ring is equipped with four X-ray pinhole cameras, of which two identical ones are used for continuous emittance monitoring and for feeding the emittance feed-back loop. The above figure 2 sketches the setup. The X-ray source point is located within the first permanent magnet dipole of a storage ring cell, having a magnetic field of 0.625 T. The pinhole itself, together with its positioning mechanics, as well as the detector block are placed in air, as this eases implementation, operation and access for maintenance. In order to limit radiation damage once the X-rays exit into air, the X-ray beam divergence in the horizontal plane is limited to 0.6 mrad by a special crotch absorber. A 100 um thin GAGG scintillator converts the X-rays into visible light, which is imaged to a CMOS camera. The whole setup can be remote controlled and aligned during operation. The pinhole magnification factor (image size/source size) is about 4, which allows to well resolve source sizes of the order of 10 um, corresponding to the operation emittance of 10 pm.rad.

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Beam Shaker

The beam shaker is a fast magnet used to apply a AC dipolar kick to the beam in order to excite betatron resonances. The bandwidth of this magnet is approximately DC - 1 MHz, which is enough to excite a few of the low-frequency betatron modes.

The magnet is located outside of the vacuum chamber, and thus special care has to be taken in order to avoid a reduction of the bandwidth due to eddy current in the vacuum chamber. Instead of using a regular stainless-steel vacuum chamber, the vacuum chamber at this location is a ceramic vacuum chamber with a thin titanium coating.

The magnet itself is made of a few copper windings printed on two PCBs. The magnet is approximately 180 mm long. There are 4 windings to generate a vertical magnetic field, required to apply an horizontal kick to the beam. To generate the vertical kick, 8 windings are used. A ferrite material is present on the outer part of the magnet. The ferrite material is the reference 8C11 from Ferroxcube[3]. With this configuration each of the two coils (for horizontal and vertical kicks) have an inductance of approximately 18 µH, which gives a good compromise between kick strength and bandwidth limitation due to the impedance of the coil at the required frequency.

Amplifier

The shaker magnet is fed by an amplifier from Amplifier research[4]. The amplifier used is the 800A3A, which can deliver up to 800 Watts of RF power (at the 3 d

B compression point) with an input signal between 10 kHz and 3 MHz.

The amplifier is located in the technical gallery, outside from the accelerator tunnel. It is connected to the shaker magnet with a 50 Ohms coaxial cable with a length of approximately 20 meters.

Noise Generator

An arbitrary waveform generator is used to generate the noise signal which will excite betatron resonances on the beam, which will then be converted in an emittance increase after dilution of the beam in the phase-space.

The waveform generator is a Keysight A33500B. It is configured to output an arbitrary waveform (with a maximum sample number of 1,000,000). The waveform generator is configured to continuously play the waveform without the need of a trigger signal to start the waveform. When the end of the waveform is reached, the waveform generator then starts again a new cycle.

[3] https://www.ferroxcube.com

[4] https://arworld.us

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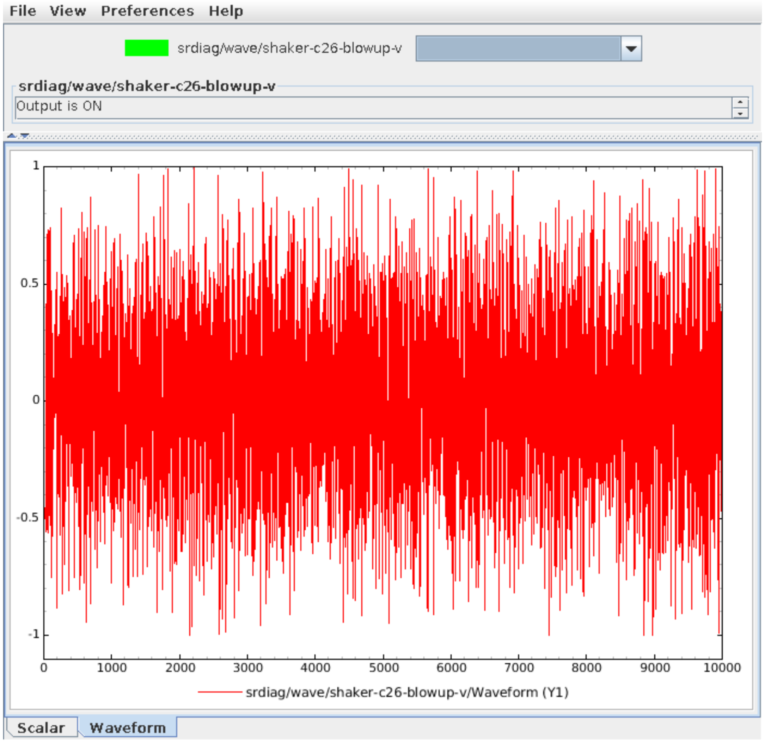

Figure 3: arbitrary signal used to excite betatron resonances

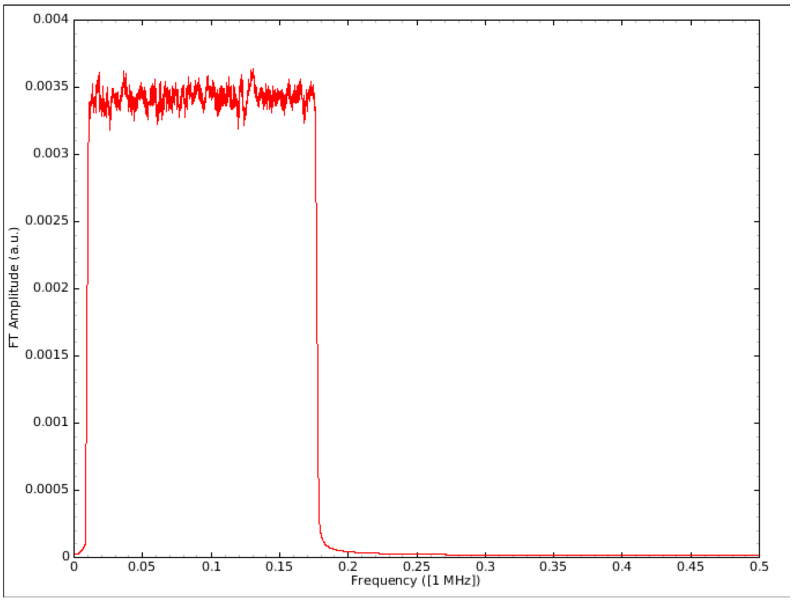

Figure 4: Fourier transform of the excitation signal

The signal was generated with a Python script in a Jupyter notebook by making the sum of multiple sine waves with frequencies which are multiples of 100 Hz, and random phases. The result is shown on Figure 3. The resulting signal has a spectrum shown in Figure 4. This signal was designed to be able to excite betatron resonances in a wide band of frequencies.

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The effect of this signal on the beam can be seen on the beam spectrum application used by the operation group of the ESRF to monitor and, if necessary, correct the tune values. This is shown on Figure 5. We can see on this graph the betatron oscillations around 125 kHz. This resonance consists of a main resonance and many smaller resonances, or sidebands, separated by the synchrotron frequency (~700 Hz). The width of the global resonance is determined by the chromaticity value, which is quite large at the ESRF as compared to similar storage rings.

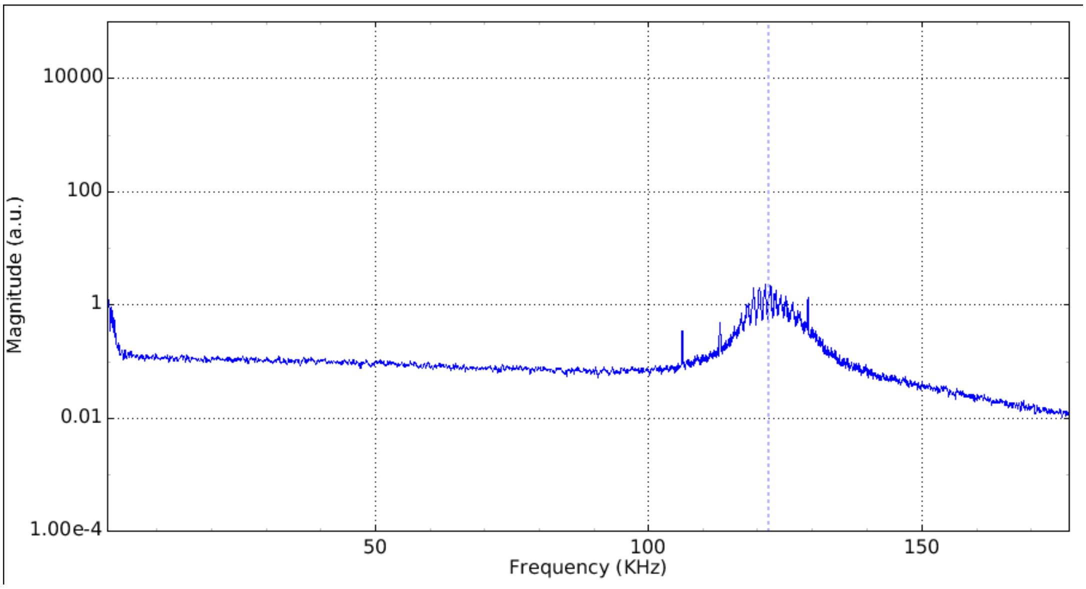

Figure 5: Vertical Beam position spectrum measured with vertical beam emittance blow-up is activated

Simulations for EBS and PETRA-IV

This section describes the simulations for EBS and PETRA-IV to evidence the effect of the shaker on vertical and horizontal emittance. A minimum chromaticity is required for the correct operation of a vertical emittance feedback system in both cases.

Simulations for EBS

At the ESRF, the vertical emittance of the beam in the Storage Ring is kept constant at 10pmrad value to increase the Touschek lifetime. The fully corrected vertical emittance is ~1pmrad. The emittance is increased using a magnetic shaker exciting the beam with a noise at frequencies including the betatron tune.

The shaker kicks the full beam with the same amplitude at each turn and the blow-up is only coming from the decoherence of the beam due to the chromaticity and the amplitude detuning. The emittance measurement in the machine is performed with a pinhole camera, integrating the signal for a few hundred turns. This means that it is impossible to understand the fraction of the measured emittance which is only coming from the average of fast coherent oscillations. Multi-particle simulations to understand the minimum value of chromaticity allowing this blow-up technique have been performed.

The multi-particle simulation is done with a simplified version of the EBS ring, including only a few elements: a 6x6 linear transformation, including the radiation damping, a nonlinear element with chromaticity and detuning with amplitude, an RF cavity, a quantum diffusion element and the shaker. The shaker is kept on and the particles are tracked for more than 32000 turns, which is several radiation damping times. The horizontal and vertical emittances are computed at each turn and the apparent emittances, using the particle positions of 10, 100 and 1000 turns, are also computed. Different repetition times of the noise signal have also been tested in the simulations.

In fig. 6, the turn by turn emittance for different vertical chromaticities are shown. On the right plot, the emittance is computed using the coordinates of 1000 consecutive turns.

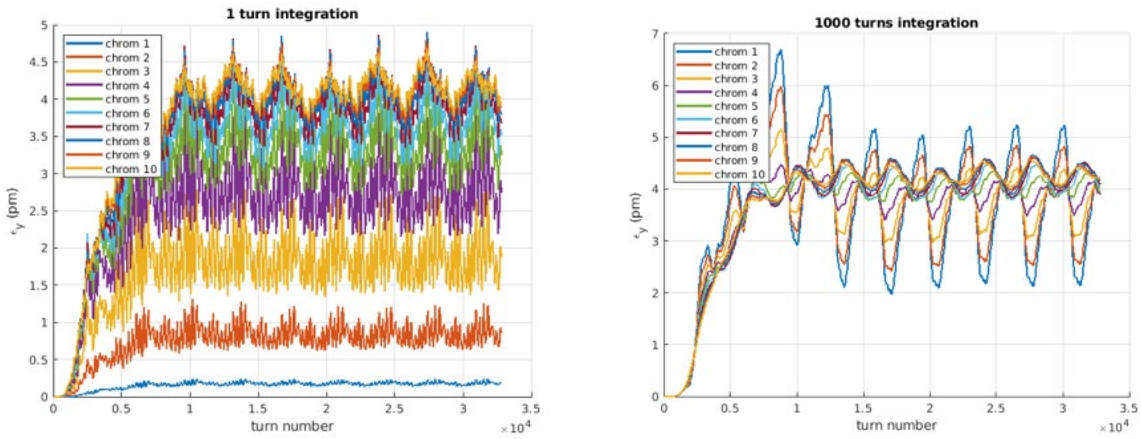

Figure 6: vertical emittance computed for multi-particle simulations at different chromaticities with vertical blow-up on. In the left plot, the emittance is computed turn by turn, in the right plot the emittance is computed using all the coordinates of the 1000 previous turns (simulating the value measurable by the pinhole camera).

The first simulation shows that at low chromaticity the emittance is not increased as much as the pinhole camera would measure integrating the signal in several hundred turns.

The residual oscillations visible, with a periodicity of about 3500 turns, are due to the repetition frequency of the noise signal sent to the shaker, which is 100 Hz in this case.

In fig. 7, the vertical emittance for three shaker amplitudes is computed turn by turn (left plot) and integrated for 10 turns (right plot) as a function of vertical emittance.

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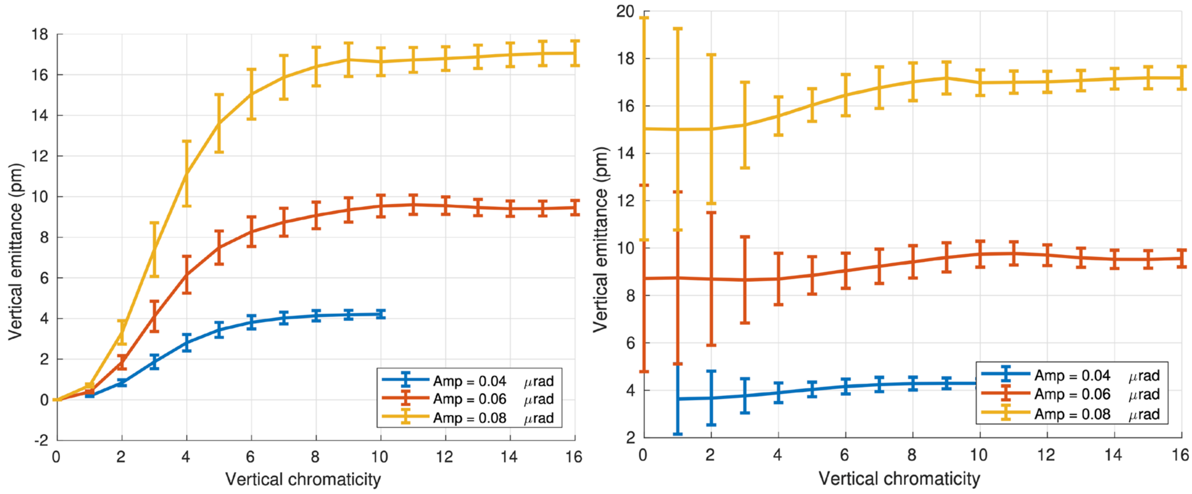

Figure 7: vertical emittance obtained with three constant shaker amplitudes as a function of vertical chromaticity. The value is the average in a few thousand turns and the error bar is the standard deviation. In the left plot, the emittance is computed turn by turn, in the right plot it is computed using the coordinates of the previous 10 turns.

With low chromaticity, most of the blow-up measured integrating for more than 1 turn is due to fast coherent oscillations. For example, with vertical chromaticity at 4 the emittance is about 35% smaller than the one that can be measured integrating the signal for many turns. If the chromaticity is 2, the emittance is about 80% smaller than the measured one.

Simulations for PETRA-IV

Compared to PETRA-III, the horizontal emittance is reduced by a factor 65 (from 1.3nm to 20pm). The vertical emittance at PETRA-III is already diffraction-limited due to extremely low coupling and will be as low as 4pm for PETRA-IV.

The simulation of emittance control is intended to answer three questions:

(1) Chromaticity range for emittance control?
(2) Kick strength required to increase the emittance?
(3) Mean orbital change when the excitation signal is applied?

The first question defines the usable operating mode for emittance control using the proposed concept with the MBFB kicker in PETRA-IV. The second question provides an answer to the kicker device, i.e. usability of MBFB stripline kickers with a maximum kick strength of 270nrad each. The third question concerns the maximum orbit changes during the increase in emittance. These should be limited to significantly less than 10% of the beam size, the total orbit stability budget.

The emittance control simulation for PETRA-IV (PIV) was done with Xsuite[5]. Those include the most recent PETRA-IV lattice including the 1st and 3rd harmonic cavities, synchrotron radiation and quantum

[5] https://xsuite.readthedocs.io/en/latest/

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excitation. Simulation were performed with 10^4 particles. The section for kicker simulation and resulting orbit and emittance change has been chosen with a vertical beta function of 7m. The excitation signal has been scanned in amplitude with variation in chromaticity. The base band of the vertical betatron resonance is set to 35.565kHz.

The beam is excited with a white noise signal as shown in time and frequency domain in Fig. 8.

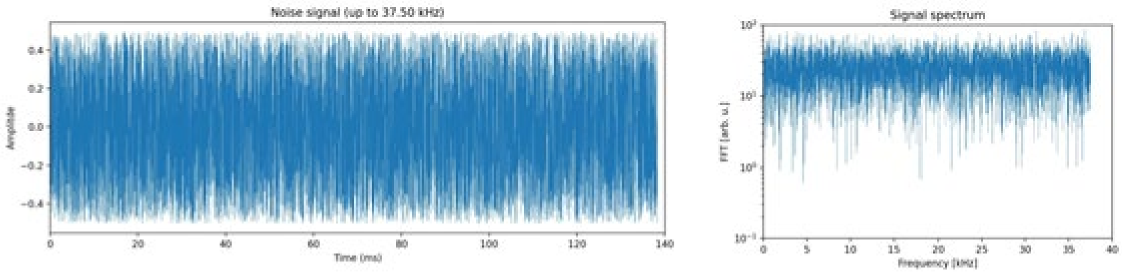

Figure 8: Kicker excitation signal in time (left) and frequency (right) domain.

In result, the vertical emittance increases as displayed in Fig. 9.

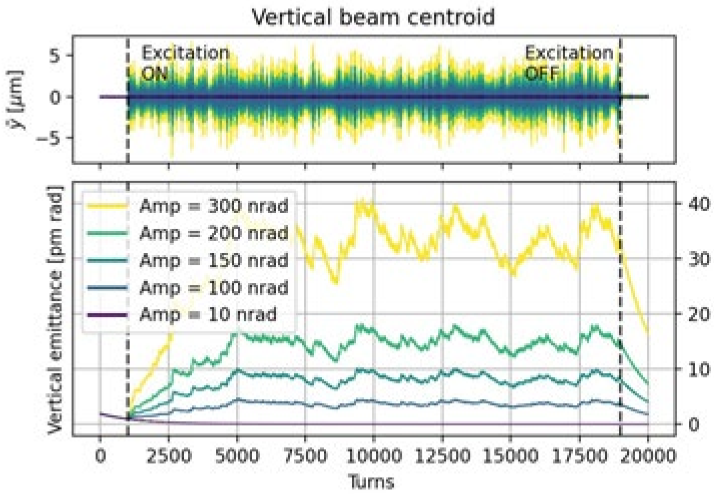

Figure 9: Mean vertical position and emittance for white noise excitation.

The excitation signal is applied for about 15.000 turns and next it is switched off. In addition to the increase in emittance, the mean vertical orbit changes by a maximum of ±5µm for the largest excitation amplitude. A mean emittance value of about 35pm rad is reached. Assuming a Gaussian distribution of the mean vertical orbit, this orbit peak value results in an effective value of about 2µm for an emittance and beta-dependent beam size of 15µm ($\sigma_y = \sqrt{\varepsilon_y \cdot \beta_y}$), i.e. about 13% of beam size variations. Here it is important to find a maximum increase in emittance that remains within the range of 10% path variation.

The simulation has been repeated with various chromaticity values and a fixed excitation amplitude of 200nrad rms deflection angle. The results are presented in Figure 10.

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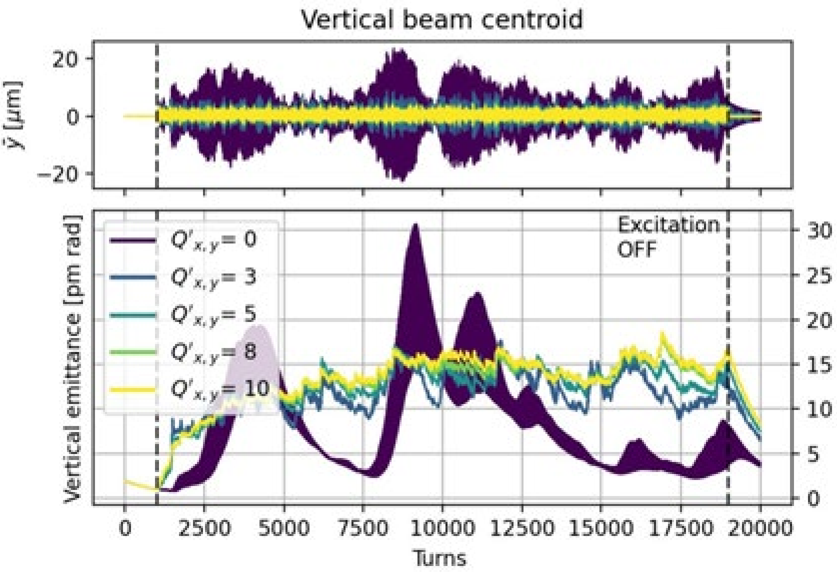

Figure 10: Mean vertical position and emittance with chromaticity variation.

Chromaticity scans were performed. Especially for the zero chromaticity, the mean orbit value is varying considerably turn by turn. Furthermore, the control of the beam emittance is not reliable for low chromaticity. The emittance control seems realizable with the chromaticity above zero leading to the stable and controllable emittance blow up. Large mean orbit variations dominate in low chromaticity operation.

The excitation signal was switched to harmonic excitation at the betatron tune in order to reduce the kick strength and the occurring fluctuations of the mean orbit. This results in an improved emittance profile compared to white noise, reducing the excitation amplitude from hundreds of nanoradians to a few tens of nano radians, see Fig. 11. Nevertheless, the mean vertical orbit deviations remain in the range of 2.1µm peak, i.e. 1.3µm rms, which is in the order of 11% for a nominal beam size of 11.8µm. With a target vertical emittance of 10pm rad, it drops to 4% of the beam size - a (barely) acceptable value for orbital distortion. Note that the betatron frequency is in the tens of kHz range, which makes the perturbation inaccessible for correction with the fast orbit feedback system.

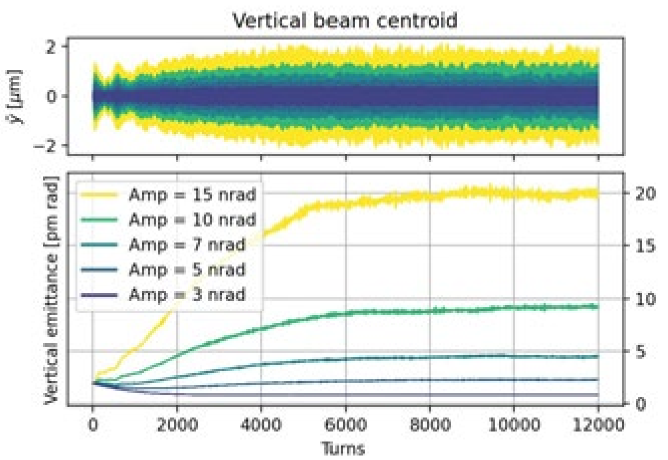

Figure 11: Mean vertical position and emittance for excitation signal around its vertical tune frequency.

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The simulations show that MBFB stripline kickers can be used for emittance control under the following conditions:

(1) Operation with chromaticity above zero
(2) Kick strength in order of tens of nano radians
(3) Mean orbital fluctuations in the range of maximum 10% of the beam size with a maximum emittance control of less than 20pm rad

Note: If the requirements for beam stability are to be reduced from 10 % to 5 % or even 3 %, the concept of emittance control with MBFB stripline kickers must be revised.

Experimental studies of vertical emittance feedback for ESRF-EBS

In order to verify the simulations of the blow-up efficiency for different chromaticities, a series of experiments has been performed at ESRF.

The emittances have been measured using the standard parameters of the pinhole camera, with an integration time of 10 ms. The apparent emittances have been measured using the BPM signal in turn by turn mode, using the beta functions at the BPM positions. Only the 128 Spark BPMs have been used, because they have a better spatial resolution than the Libera.

The emittance blow-up feedback was set at different values: the vertical at 0, 20, 40, 60, 80, 100 and 120 pm; the horizontal at 7 different values from 130 pm to about 400 pm. The turn by turn position of the beam has been acquired 5 times for 10000 turns for each emittance value. The measurements have been repeated for different values of horizontal and vertical chromaticities: from 10, 8, 6, 4, 2 and 0.

The filling mode during the measurement was multi-bunch 1/3, so about 300 bunches were filled, with 10 mA total current.

In fig. 12 and 13, the apparent horizontal and vertical emittances[6] measured with the BPMs as a function of the horizontal and vertical emittances measured with the pinhole camera are shown for different chromaticities.

[6] Apparent emittances are the observable emittance from a pinhole camera setup.

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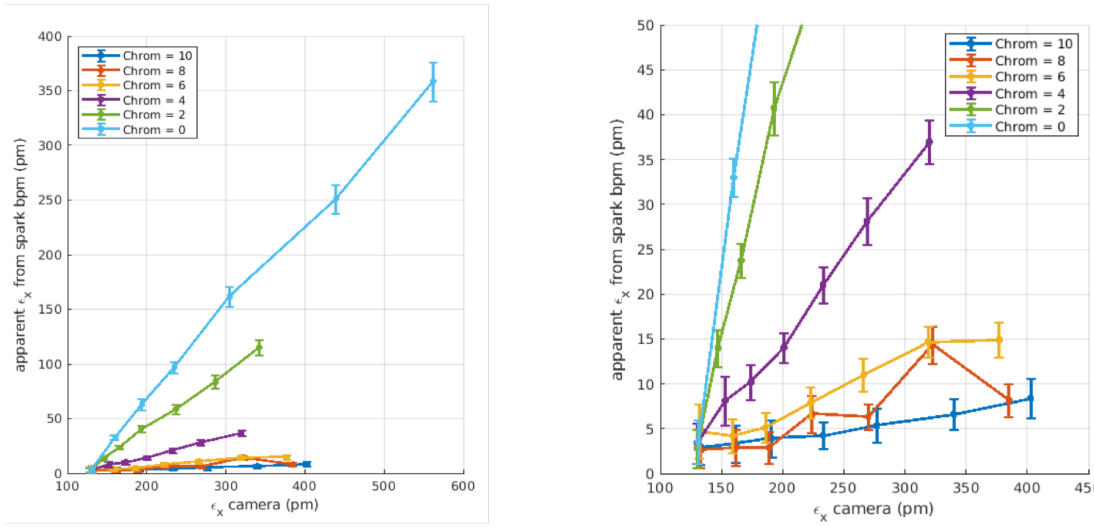

Figure 12: measurements of apparent horizontal emittance from the BPM as a function of the measured horizontal emittance from the pinhole camera for different horizontal chromaticities. The plot of the right is a zoom of the one on the left.

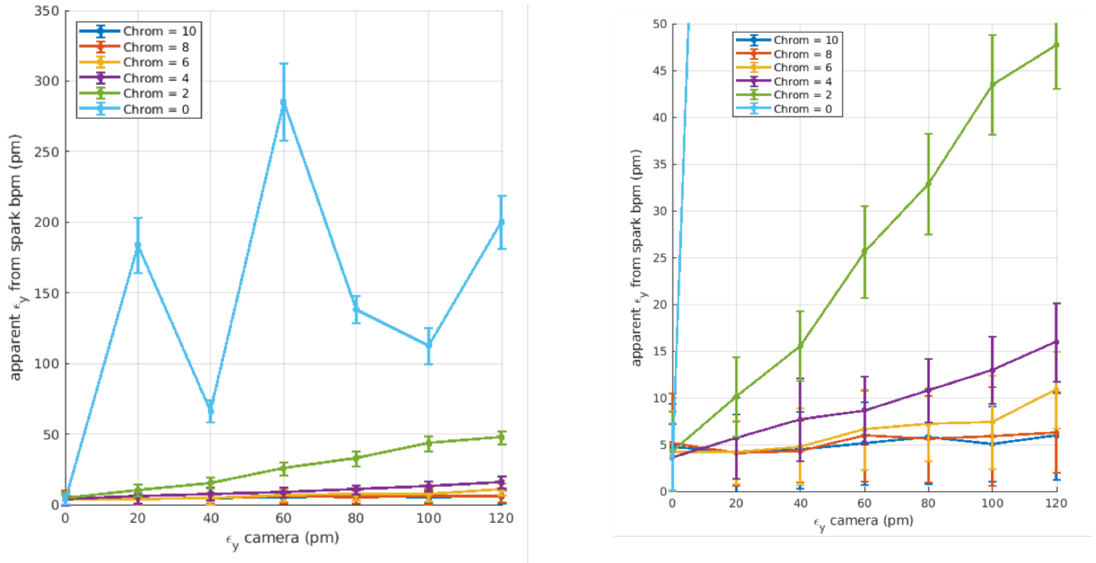

Figure 13: measurements of apparent vertical emittance from the BPM as a function of the measured vertical emittance from the pinhole camera for different vertical chromaticities. The plot of the right is a zoom of the one on the left.

In fig. 14, the fraction of the emittance measured with the pinhole camera that is coming from the center of mass coherent oscillations is shown for different chromaticities.

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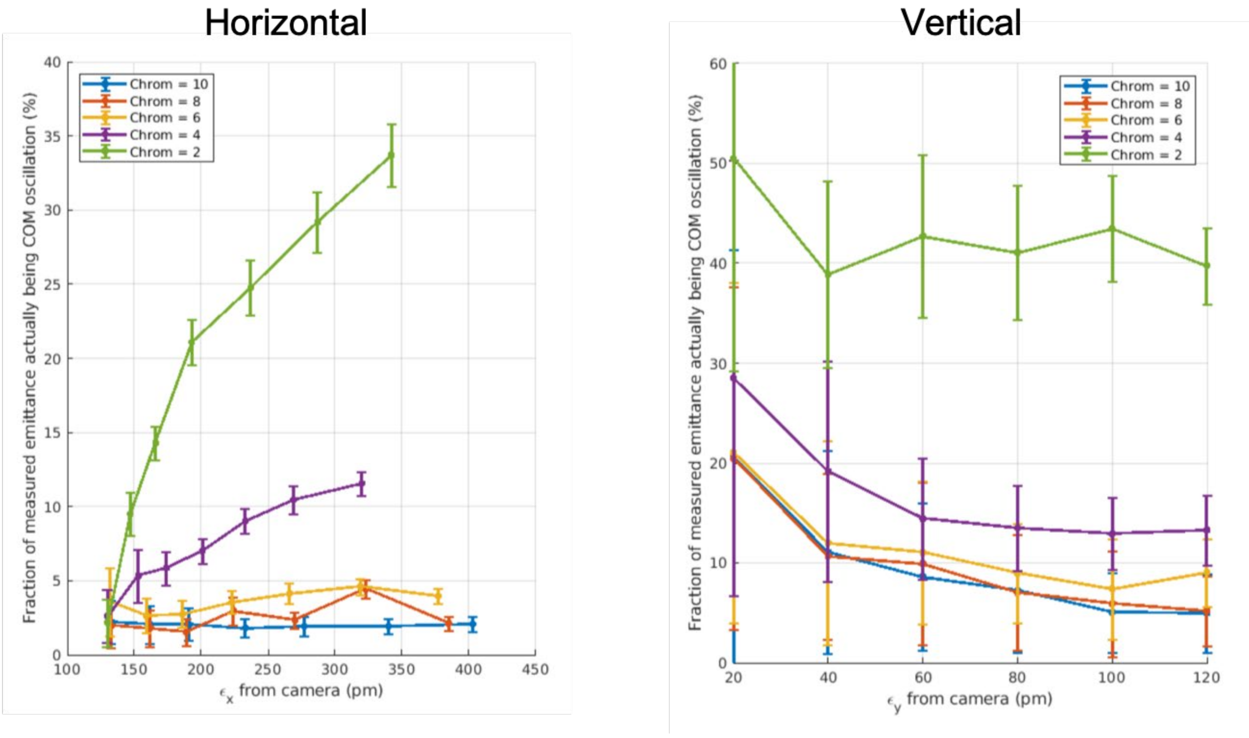

Figure 14: fraction of horizontal (left) and vertical (right) emittance that is just average of fast coherent oscillations as a function of emittance measured with the pinhole camera.

The measurements performed at the EBS storage ring confirmed the results of the simulations. Even with no excitation, the measured apparent emittance from the BPMs is in the order of a few pm, coming completely from the noise of the BPM signals. This puts some limits on the precision of the measurements.

With chromaticity equal 4, the vertical apparent emittance measured with the BPMs is on the order of 30% of the one measured with the pinhole camera at 20 pm and about 15% at 60 pm.

Emittance measurement system at PETRA-IV

Emittance diagnostics in PETRA IV will be challenging. In order to resolve the horizontal (vertical) beam emittance of about ε = 18 (2) pm.rad (brightness mode with 0.1 mA bunch current), a beam size resolution of 0.1 µm is envisaged.

Taking into account diffraction broadening of synchrotron radiation and the specific geometry of PETRA, the requested sensitivity can be achieved only with radiation emitted in the X-ray spectral region which requires a dedicated diagnostics beamline. Considering operational aspects of the storage ring which require beam size measurements over a wide range, two interchangeable monitor concepts will be realized for different ranges with different resolutions. Working horse will be an X-ray pinhole camera (XPC) because it is a simple and robust method for beam profile measurements above ~10 µm, however at the expense of limited resolution. In order to achieve a high-resolution measurement for beam sizes in the range between 1-20 µm, X-Ray Fresnel diffractometry (XFD) is

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planned. Both monitor concepts will be realized in a single diagnostics beamline[7]. The overall beamline length is about 45 - 50 m and allows the installation of detector and monochromator outside the accelerator tunnel in a dedicated optics hutch. This is advantageous because it allows easy access and maintenance even during machine operation which is of importance for the emittance feedback.

The pinhole monitor which uses the full synchrotron radiation spectrum will be installed in a dedicated target chamber onto a goniometric stage. This allows a precise target adjustment and to move the pinhole out of the optical path in the case that the XFD monitor is used. The source-target distance of 13 m provides a high X-ray magnification and thus good resolution: the pinhole aperture, optimized for a photon energy of 16 keV, amounts to 26 µm and the resulting PSF rms size is 14 µm.

In order to achieve a high-resolution measurement, X-Ray Fresnel diffractometry (XFD) has been considered[8]. The principle idea is to operate a pinhole-like structure (aperture) in the Fresnel regime, i.e. in close distance to the detector such that a double-lobed diffraction pattern emerges while the beam size information is encoded in the smearing out of its central dip. The aperture size A resulting in an optimized diffraction pattern depends on the wavelength of observation, the distance between source point and aperture L, and the distance between aperture and detector R. Given the PETRA IV requirements, it is planned to place the aperture at L = 27 m from the radiation source and the detector at R = 18 m from the aperture selecting a photon energy of 16 keV; for these parameters the optimized aperture value is A = 77 µm. This system is able to detect 100 nm beam size variation in a range between 0.9 µm and 18 µm assuming a camera sensor with 10 effective bits. Again, the aperture will be housed in a dedicated target chamber onto a goniometric stage which allows a precise target adjustment and to move it out of the optical path in the case that the XPC monitor is used. The XFD scheme requires monochromatic X-rays, therefore a single crystal monochromator using Silicon (111) is considered since it generates a photon bandwidth narrow enough (~10^{-4}). Together with the detector setup the monochromator will be housed in the optics hutch.

In the first stage of PETRA IV however (i.e. for the first two years after start of the machine commissioning), the hutch and with it the monochromator setup will not be available. In this situation the XFD monitor which requires a monochromatic photon beam will not work, and machine operation fully relies on the XPC system. In order to meet the resolution requirements, the pinhole has to be installed at a distance as close as possible to the radiation source point in order to increase the magnification. This can be realized by operating the pinhole in air: with a minimum source-to pinhole distance of about 7.5 m, a magnification of ~5 can be achieved.

The transverse beam size not only depends on the emittance but also on the relative momentum spread. Online control of the momentum spread $\frac{\Delta p}{p}$ is of utmost importance for the operation of PETRA

[7] M. Marongiu, G. Kube, M. Lantschner, A.I. Novokshonov, and K. Wittenburg, Emittance Diagnostics at PETRA IV, in Proc. 11th Int. Beam Instrum. Conf. (IBIC'22), Krakow, Poland, Sep. 2022, pp. 430-433.

[8] M. Masaki, S. Takano, M. Takao and Y. Shimosaki, X-ray Fresnel diffractometry for ultralow emittance diagnostics of next generation synchrotron light sources, Phys. Rev. ST Accel. Beams, vol. 18, no. 4, p. 042802, 2015.

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IV, therefore a measurement of this parameter is additionally required. With knowledge of the beam optical parameters (β-function and dispersion), a single beam size measurement is not sufficient in order to extract the two unknown parameters $\varepsilon, \frac{\Delta p}{p}$. Therefore, a second measurement, and with it a second diagnostic beamline, is required. With two beamlines at locations with different dispersion, it is possible to extract both transverse beam emittance and relative momentum spread.

Both diagnostic beamlines in PETRA IV will be installed in the canted straight section of P49 in the northern part of hall PXW. Using two 3-pole wigglers as radiation sources following the ESRF design (peak magnetic field 0.8 T, period length 81 mm, critical energy ~19.1 keV, total radiated flux 332 W) and a canting angle of ±2.5 mrad it is possible to generate two beamlines with sufficient difference in the dispersion that can share one optics hutch.

Feedback system foreseen for PETRA-IV

The previous simulations have shown that emittance control is possible with only one kicker in the vertical plane. However, this also led to orbit variations whose influence depends on the emittance target. This is a limitation when using the MBFB kicker as an actuator for emittance control (as defined in the milestone). Emittance control can therefore only be realized to a limited extent with the MBFB kicker. We are investigating how this can be improved.

A transverse multi bunch feedback (MBFB) system for PETRA IV is being planned[9]. The system will consist of 4 stripline kickers each with the maximum kick angle of 270nrad. The stripline kicker electrodes will be as short as 30cm to avoid any bunch-to-bunch coupling for bunch spacing down to 2ns. The digital system is currently under design using the RFSoC as the main processing unit. The FPGA will control DACs, working with the maximum clock frequency of 10GSPS to provide an excitation to the kicker. Each DAC drives a high-power amplifier, which is connected to a stripline kicker. Such a system allows to separate kickers into different tasks, e.g. 1 kicker can be used for the emittance control and the others for the bunch-by-bunch feedback. The conceptual block diagram is shown in Fig. 15.

In the main processing FPGA, a firmware module for white noise generation together with a digital filter is foreseen. This allows to shape the white noise signal into either a bandwidth limited or narrow band excitation signal. The amplitude of the noise signal can be set externally, e.g. by a front-end server using the emittance deviation from target value for feedback. Coupling effects between the transverse multi bunch feedback and the emittance control system using the same or a separate actuator need to be considered in the future.

[9] http://doi.org/10.18429/JACoW-IBIC2022-WEP36

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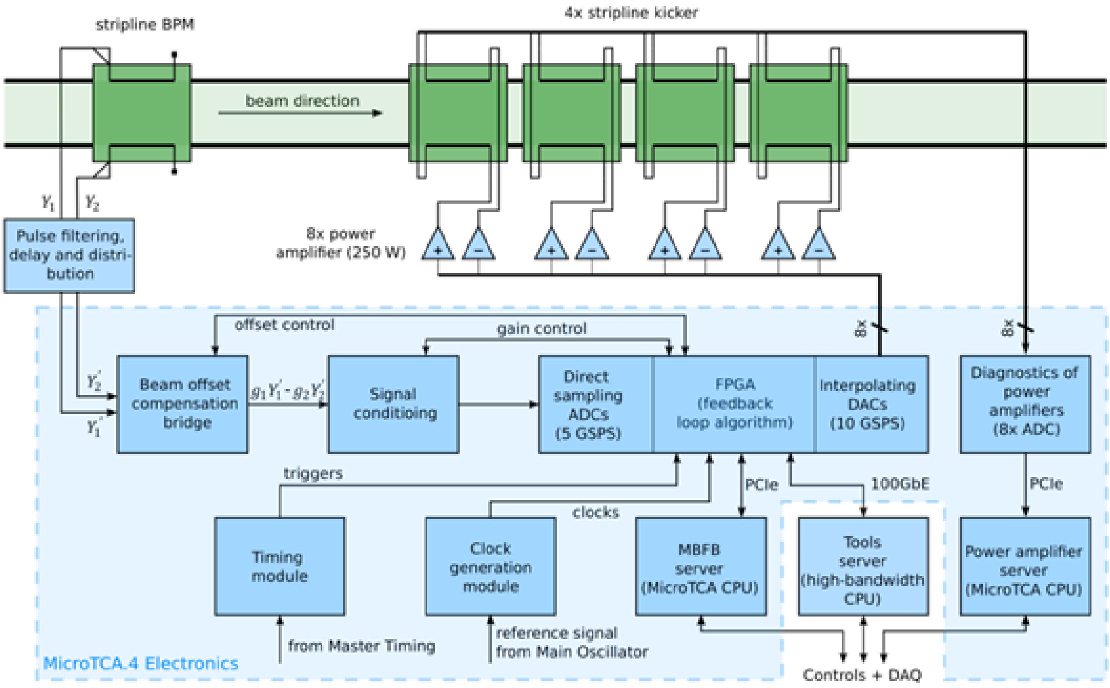

Figure 15: Simplified block diagram of the vertical transverse multi-bunch feedback.

Conclusion

Following the experience of EBS in setting up a vertical emittance feedback several studies have been performed to specify the operational conditions of such a system and implement it for the proposed PETRA-IV upgrade. The specifications for a vertical emittance feedback for PETRA-IV described in the above document may be summarized as:

- Chromaticities higher than 3 units are required. 6D multiparticle tracking simulations show that chromaticities higher than 6 units are required for EBS storage ring and higher than 0 units for the PETRA-IV storage ring to generate 90% of the vertical emittance observed at pinholes. Lower values, such as 0 chromaticity imply that more than 50% of the observed vertical beam emittance at the pinholes is actually a fast coherent vertical beam motion rather than emittance blow up. These simulations were confirmed by beam measurements in the EBS storage ring.
- The PETRA-IV pinhole emittance monitors are suitable to act as measurement for the feedback.
- The strip-line shakers already planned for the MBFB system of PETRA-IV provide a sufficiently large angular kick and frequency range.
- Larger orbit deviations are to be expected in the emittance control with the MBFB system, i.e. there will be an emittance limit to stay within the 10% beam size variations.

Planned publications:

IPAC 2024 Nicola Carmignani et al. abstract has been submitted.

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