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FEW-NANOSECOND STRIPLINE KICKERS FOR TOP-UP INJECTION INTO PETRA IV

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Abstract

PETRA IV is the planned ultralow-emittance upgrade of the PETRA III synchrotron light source at DESY, Hamburg. The current baseline injection scheme is an off-axis, top-up injection with few-nanosecond stripline kickers, which would allow for accumulation and least disturbance of experiments during injection. Besides the requirements on kick-strength, field quality, pulse rise-rate, and heat management, two mechanical designs with different apertures are necessary, as the devices will be used for injection and the transverse multi-bunch feedback system. In this contribution we will present the current status of 3D finite element simulations of electromagnetic fields as well as the mechanical design and first pulse electronics tests.

INTRODUCTION

Several major lightsources have recently been upgraded or are currently undergoing an upgrade to so-called 4th generation light sources, which approach the diffraction limit of the produced synchrotron light with ultra-low emittances in the range of a few 10 pm to 150 pm. One difficult aspect of the beam optics of such low-emittance storage rings is a very limited dynamic aperture. This hinders top-up injection of bunches into the machine and has led to the choice of a full-charge swap-out injection scheme in most designs.

The PETRA IV project aims at upgrading the PETRA III 6 GeV synchrotron radiation facility into a 4th generation light source [1]. Simulations indicate that in PETRA IV top-up injection is nevertheless possible and it is currently pursued as the baseline injection scheme. To limit the impact of an injection event on the stored beam, the kickers in PETRA IV are designed to have a kick duration equal to the target bunch separation of 2 ns. This is only achievable with short stripline kickers, which are being developed for this purpose at DESY. First simulations of the electromagnetic design of these devices have been presented before [2]. In this contribution we will give an update on the kicker magnet requirements for single-bunch top-up injection, show the updated electromagnetic design, and go into some details of the mechanical design and pulse electronics development.

INJECTION KICKER REQUIREMENTS

The stripline design had to be adjusted to the new baseline top-up injection scheme from the original swap-out injection of 80 ns bunch trains. To not constrain the dynamic aperture of the storage ring, the free aperture of the striplines has to be at least 16 mm in diameter. Stripline length and high voltage (HV) pulse duration define the kick strength on neighbouring bunches, which are not being injected into. This residual kick shall be minimised for least disturbance of user experiments during injection. On the other hand, shortening the striplines also reduces the absolute kick strength of one kicker module and ultimately results in a very large number of modules, making injection increasingly complicated. Additionally, the length of every kicker module should be used efficiently. Figure 1 shows analytical calculations for all these criteria. In Fig. 1 (a) half of the assumed, time-symmetric input HV pulses is depicted for several assumed pulse lengths. The absolute kick angle for different lengths is shown in Fig. 1 (b). Efficiency of length usage is judged upon by the relation between actual kick angle and the maximum possible kick angle at a certain voltage and stripline length, which is shown in Fig. 1 (c). Finally, the kick strength on a neighbouring bunch at 2 ns separation relative to the nominal kick strength is shown in Fig. 1 (d).

Based on these calculations, a stripline length of 0.35 m with a flat top pulse length of 2 ns was chosen. The assumed rise and fall times are 0.5 ns.

With these theoretical parameters a total of 16 stripline kicker modules (plus 4 spare modules) would be required for a 4-kicker bumped orbit at the Lambertson-type injection septum in the current lattice design. Pulse voltage has to be adjustable within a range of (8-14) kV in order to provide the required kick strength at the four different positions as well as a certain adjustment range and redundancy.

ELECTROMAGNETIC DESIGN

Simulations of the electromagnetic behaviour of the striplines are performed using CST Microwave Studio. The simulations have been integrated into a Bayesian optimisation routine to allow complex geometry optimisation [2]. The cross-section geometry is shown in the lower right of Fig. 2. A symmetric aperture of 16 mm in diameter is kept free between the stripline blades and the side fenders, which are introduced to reduce capacitive coupling between the blades. The same cross-section geometry is also planned to be used for the striplines of the transverse multi-bunch feedback system of PETRA IV.

In the end sections of the stripline blades, not only the optimal electromagnetic design has to be taken into account, but also constraints as e.g. possibilities for mechanical adjustment of the stripline positions have to be considered. A first optimisation of this has been performed for a prototype of the PETRA IV injection kickers. Simulated reflected pulses at the rising and falling edge of the input current of this prototype exhibit a maximum of 4 % of the incoming

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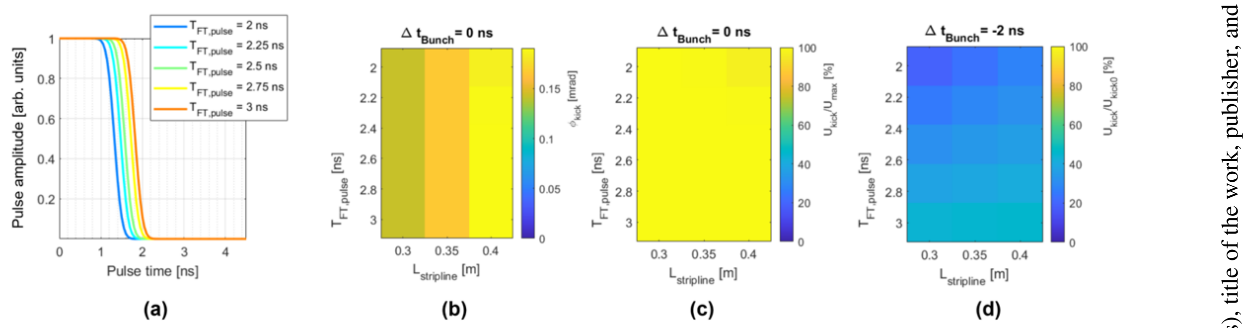

Figure 1: Analytical calculation of stripline length and pulse shape constraints. Assumed pulse shapes are shown in (a), the absolute kick strength at 12 kV/6 GeV is shown in (b). The kick strength relative to the maximum kick strength possible for the given length (peak amplitude during full passage duration of the kicked bunch) is shown in (c) and (d) shows the kick strength onto a bunch with 2 ns delay relative to the nominal strength given in (a).

amplitude. Further optimisation of the setup is still ongoing, especially with respect to the longitudinal and transverse beam impedance of the kickers as a single module and in an arrangement of several modules in a row. One possible approach that is considered here, which has been presented for feedback striplines, but not for injection kicker setups so far, is the introduction of additional capacitance at the stripline blade ends, to suppress the excitation of higher order modes [3].

MECHANICAL DESIGN

The mechanical design of the first prototype of the PETRA IV injection kickers is shown in Fig. 2. Due to several changes of the mechanical requirements in the last months, this prototype still exhibits an aperture of 14 mm in diameter and as this setup is envisaged to be used for measurements as an injection kicker and as a feedback kicker, the length between the two contacts of the electrodes, i.e., the distance between the central pins of the vacuum feedthroughs of one stripline blade is 0.3 m. The basic approach for the design was to use the outer conductor of the stripline as a vacuum vessel, unlike other recent designs [4–6]. This less complex mechanical design was chosen to enable a simple combination of different numbers of stripline kicker modules at the various kicker positions. Vacuum levels are planned to be ensured by non-evaporable getter (NEG) coating of the inner surfaces of the kicker. The outer tank has a DN63 CF flange connector on either end, which is machined from bulk steel material and vacuum feedthroughs are integrated into it. This reduces the gap between two sets of electrodes to < 14 mm, depending on the excess length of the electrodes extending outwards from the feedthrough connectors.
Weldable feedthroughs from CeramTec have been acquired and their DC breakdown voltage has been measured. A maximum hold-off voltage of 15 kV was found in these tests at a pressure of ca. 10^{-7} mbar. Operation voltage was thus constrained to 14 kV, with an extra safety margin due to the short duration of the HV pulses used during operation. Dielectric losses were measured at 1 GHz, 300 W and only a minor temperature increase of ca. 20 °C was found. Time dependent reflectometry (TDR) measurements were performed and showed tolerable levels of reflection.

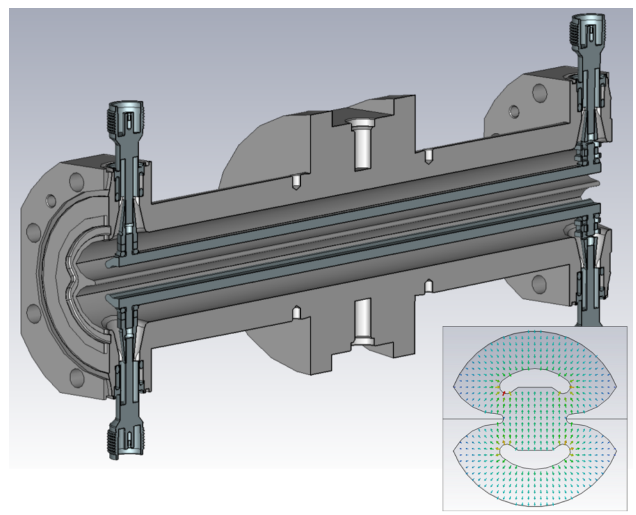

Figure 2: Mechanical design of the prototype PETRA IV stripline kicker. Inset in the lower right shows the cross section geometry.

A sliding contact has been introduced at one end of each electrode, to prevent excessive mechanical stress on the vacuum feedthroughs when the electrodes are heating up during vacuum baking or due to induced currents from the high average current, stored beams. Electrodes will be made of tungsten to minimise thermal expansion while maintaining good electrical and thermal conductivity. By using a two-threaded nut and an RF spring, the stripline blades can be adjusted in height . No additional adjustment in transverse direction is foreseen at the moment other than the exact placement of the vacuum feedthroughs.

PULSE ELECTRONICS

The changed requirements on the PETRA IV injection kicker from bunch train to single-bunch top-up injection has also changed HV pulse requirements. Ground-symmetric HV pulses have to be supplied to the stripline electrodes,

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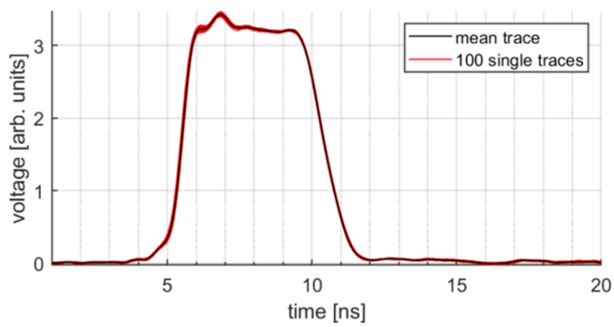

Figure 3: Single and averaged current traces measured with a 4 ns test pulse from FID GmbH.

each of which are matched to an electrical impedance of 50 Ω in the odd mode, i.e., opposite polarity of the two electrodes. A development project has been initiated with the high power electronic systems group at the ETH Zurich, to explore the pulse rise and fall time limits of available semiconductor HV switch components and different circuit topologies. Preliminary results indicate that Marx generator and linear transformer driver (LTD, also called inductive adder) topologies enable similar switching times in the range of ca. 3 ns to 12 ns with some slight disadvantages in the rise times and advantages in the fall times for the LTD due to additional parasitic inductances in the switching circuit [7, 8]. Further studies include the application of advanced gate circuitry to these switches to probably increase switching speed slightly [9, 10], whereas the required switching times of ca. 0.5 ns seem to be inaccessible. Therefore, a test pulse system from FID GmbH based on drift step recovery diodes (DSRDs) [11] has been received and tested for pulse stability, rise and fall times, and also for kick tests with an existing, 2 m long stripline kicker at the European XFEL. This pulser was designed for a pulse length of 4 ns and exhibited rise and fall times of ca. 1 ns and 2 ns, respectively. Figure 3 shows 100 current traces measured with a 5 GHz bandwidth, 10 GS/s Tektronix oscilloscope using an FID 40 dB attenuator and an API/Weinschel 53-40-33 40 dB attenuator at the upstream end of a European XFEL-type, 2 m long stripline kicker.

The measured timing jitters were around (30–40) ps with no significant dependence on temperature or operation time. It should be noted that the measured timing jitter is of the same order of magnitude as the measurement resolution. Beam positions of bunches deflected using this combination of an existing kicker and the FID test pulser are shown in Fig. 4. In the recorded positions at 3 different downstream beam position monitors (BPMs) the same behaviour is seen: the deflection rises at a timing delay between ca. (60–40) ns and levels at a peak deflection with only minor dependence on the delay. This minor dependence is due to the bunches being deflected at a position more upstream in the stripline and therefore a larger drift distance to the BPM. This slope therefore also becomes less pronounced when measuring at BPMs further downstream.

At later other delays (< 40 ns) two more deflection peaks

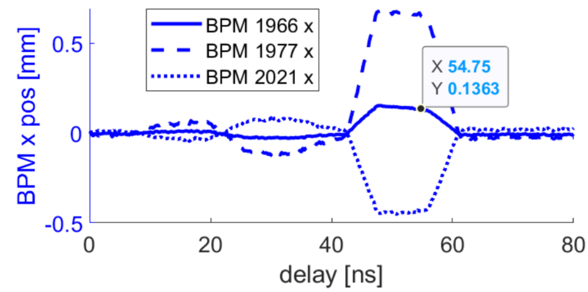

Figure 4: Measured transverse bunch positions for bunches deflected using a 2 m long stripline kicker at the European XFEL and the HV pulses shown in Fig. 3. The positions are measured at three different positions downstream the kicker position at 1960 m in the XFEL beamline, with the exact measurement positions given in the legend. For the two positions further downstream, several quadrupole magnets were used in between the kicker and the measurement position.

were measured. The exact cause of these peaks is yet to be understood, but probably internal reflections due to insufficient electrical matching are responsible for this behaviour. Such reflections have been observed in TDR measurements and are likely caused by several ceramic support stems and vacuum ports in the stripline setup.

SUMMARY AND OUTLOOK

Stripline kickers are being developed to enable single bunch top-up injection in PETRA IV. The simulated residual kick strengths on bunches upstream and downstream of the kicked bunch are below 25 % of the nominal kick strength. A total of 3 bunches out of >3000 stored bunches are expected to be disturbed. It is also planned to use a similar kicker design for the transverse multi-bunch feedback system of PETRA IV. Currently, a first prototype is being built and measurements are planned for the early second half of 2022. Based on the experiences with this first setup, dedicated prototypes of the final injection and feedback kicker will be built and shall be tested under operational conditions in an existing storage ring before production of the required ca. 20 injection kicker modules and up to 16 feedback kicker modules.

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