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

The brightness of the synchrotron radiation produced at storage ring light sources as well as its transverse coherence largely depends on the emittance of the stored particle beam. 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 makes top-up injection of bunches into the machine very difficult and in most machines has led to the choice of a full-charge swap-out injection scheme.
One such upgrade is the PETRA IV project, which 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 still possible and it's 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 pulse length 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 which have become necessary for the single-bunch top-up injection scheme, will then show the updated electromagnetic design, and go into some details of the mechanical design and pulse electronics development.

INJECTION KICKER REQUIREMENTS

Originally, a swap-out injection of 80 ns long bunch trains was foreseen for PETRA IV. Since top-up injection was deemed possible and is now the baseline design, the design of the stripline injection kickers has to be adjusted. 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. The stripline length and duration of the used high voltage (HV) pulse 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, which makes tuning of the injection very difficult. At the same time it has to be ensured that the length of every kicker module is 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 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. Additional modules are planned to be installed at all four positions to compensate for failure of any one module during operation.

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]. A first step in the overall optimisation was to achieve the best possible matching between even and odd excitation mode impedances of the kicker, simultaneously with a high field quality by adjusting the parameters of the cross-section

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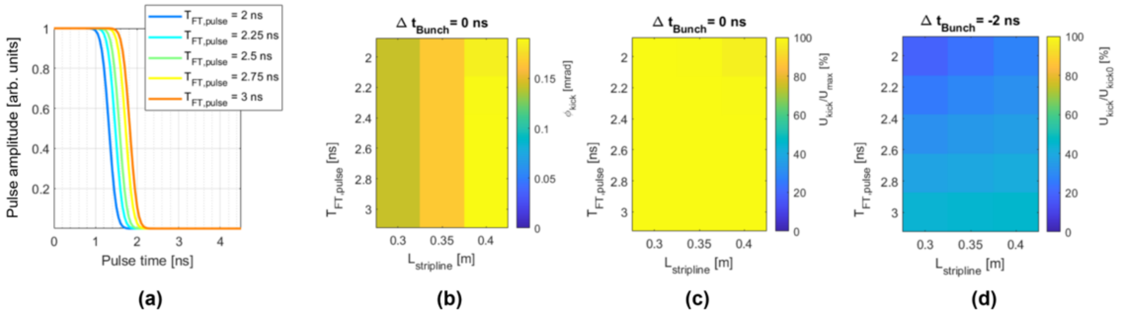

Figure 1: Analytical calculation of stripline length and pulse shape constraints. Assumed pulse shapes are shown in (a), the absolute kick strength at 12 kV/6 GeV is shown in (b). The kick strength relative to the maximum kick strength possible for the given length (peak amplitude during full passage 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).

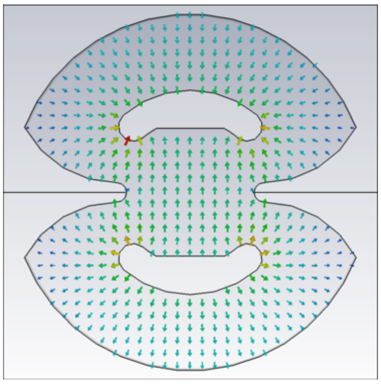

Figure 2: Optimised cross-section geometry of the PETRA IV stripline kickers. Arrows indicate electrical field in the odd mode excitation (opposite polarity stripline electrodes, outer conductor on ground potential).

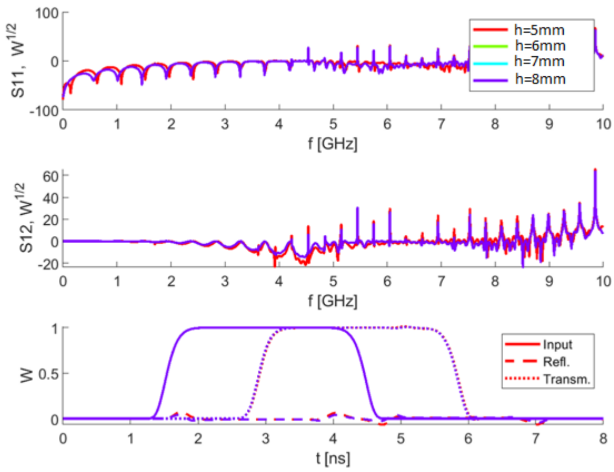

Figure 3: Simulated S-parameters (top and centre plots) and ingoing, reflected, and outgoing pulses (bottom plot) of the stripline prototype setup for different heights h of the custom connection nuts (see Fig. 4, lefthand end of blades).

geometry. The final geometry is shown in 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. As these are placed at a position of maximum beta-function, the aperture here as to be 26 mm in diameter and the cross-section design will be linearly scaled up to meet this.

A more complex endeavour has to be taken to optimise the geometry of the ends of the striplines. In this section not only the optimal electromagnetic design has to be taken into account, but also constraints as 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. The result of this optimisation in terms of electrical transmission and reflection in the whole stripline setup is shown in Fig. 3. S-parameters for reflection and transmission for a frequency range up to 10 GHz are shown in the top and centre plot, respectively. The lower plot shows the input, reflected and transmitted pulses in solid, dashed and dotted lines, respectively. Reflected pulses at the rising and falling edge of the input current exhibit a maximum of 4 % of the incoming amplitude, which does not depend strongly on the input connection geometry, as results for different sizes of the connector suggest.

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 magnets 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. 4. Due to several

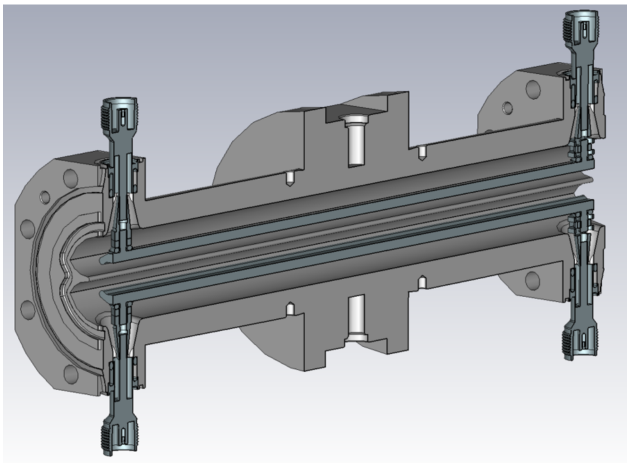

Figure 4: Mechanical design of the prototype PETRA IV stripline kicker.

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 flange connector similar to a CF63 flange on either end. This flange is machined from bulk steel material and to ensure the closest possible proximity between the electrodes of two adjacent kicker modules, the vacuum feedthroughs are integrated into the flange. The gap between two sets of electrodes is thus reduced to a maximum of 14 mm, depending on the excess length of the electrodes extending from the feedthrough connectors towards the ends.

Weldable feedthroughs from CeramTec have been acquired and several tests have been performed to evaluate their suitability for this application:

1. Breakdown voltage has been measured with a DC HV source. 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 compared to the DC test voltage.

2. Dielectric losses were measured at 1 GHz, 300 W and only a minor temperature increase of ca. 20 °C was found.

3. Time dependent reflectometry (TDR) measurements were performed to evaluate the electrical matching of the feedthroughs. Minor mismatch was found with main reflections coming from the used connectors.

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, e.g., 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 in the first place while maintaining good electrical and thermal conductivity. By using a two-threaded nut with an additional nut for fixation and an RF spring to ensure good electrical contact, the stripline blades can be adjusted in height (i.e., their distance from the feedthrough). No additional adjustment in transverse direction is foreseen at the moment other than the exact placement of the vacuum feedthroughs. Simulated tolerances of (50–100) μm are in the range of the expected manufacturing tolerances.

PULSE ELECTRONICS

The changed requirements on the PETRA IV injection kicker from on-axis injection of bunch trains to single-bunch top-up injection has also largely changed requirements on the HV pulsers. Ground-symmetric HV pulses have to be supplied to the stripline electrodes, 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 limits of available semiconductor HV switch components and a circuit topology, to achieve the shortest possible rise and fall times of the produced pulses. Preliminary results of this ongoing project are 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]. The switching speed is mainly limited by the silicon-carbide (SiC) MOSFET switches that are commercially available [8].

Further studies will concentrate on applying advanced gate circuitry to these switches to probably increase switching speed slightly [9, 10]. Nevertheless, it is not expected that available semiconductor switches will allow the required switching times of ca. 0.5 ns. 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 5 shows 100 current traces from the acquired test pulser along with the average trace. Current traces were measured with a 5 GHz bandwith, 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,

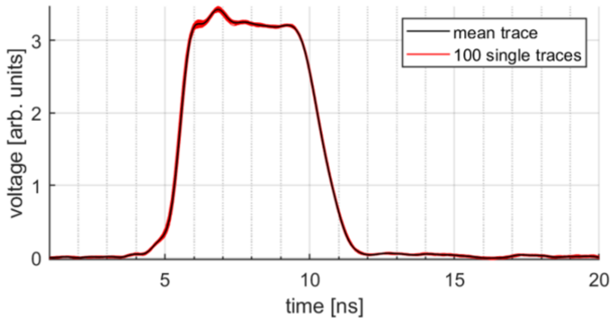

Figure 5: Single and averaged current traces measured with a 4 ns test pulse from FID GmbH.

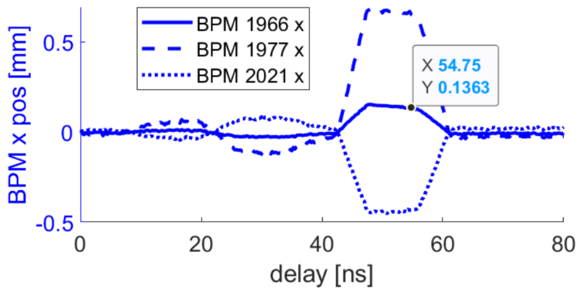

Figure 6: Measured transverse bunch positions for bunches deflected using a 2 m long stripline kicker at the European XFEL and the HV pulses shown in Fig. 5. The positions are measured at three different positions downstream the kicker position at 1960 m in the XFEL beamline, with the exact measurement positions given in the legend. For the two positions further downstream, several quadrupole magnets were used in between the kicker and the measurement position.

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 measured jitter of the trigger signal and likely influenced by the measurement resolution. Beam positions of bunches deflected using this combination of an existing kicker and the FID test pulser are shown in Fig. 6. 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 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. In the TDR measurements of the European XFEL type striplines shown in Fig. 7, several reflection peaks at the two electrodes

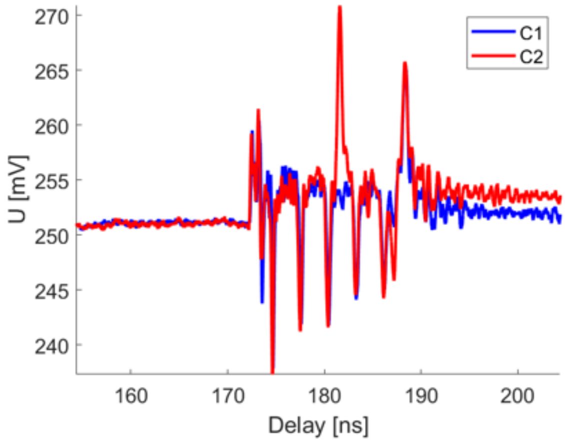

Figure 7: TDR measurement trace of the European XFEL 2 m long stripline kicker. Several reflections are measured which are attributed to sources of electrical impedance mismatch like ceramic support stems (negative peak amplitude) or the single-sided vacuum pumping port (positive peak at ca. 182 ns delay).

are visible, which are caused by multiple 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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