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DEVELOPMENT OF FAST AND SUPER-FAST KICKER SYSTEM FOR SLS 2.0 INJECTION

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Abstract

Swiss Light Source plans a major upgrade to turn the existing Storage Ring (SR) into a modern diffraction limited light source called SLS 2.0. As part of this project, the injection system has to be upgraded as well in order to ensure reliable and efficient injection in the reduced beam aperture. A 4-kicker bump and new thin septum will ensure the conventional injection in the SR. To further minimize the perturbation of the stored beam during injection two new schemes are in development: "Fast" and "Super-fast" one. The "Fast" injection scheme should be able to ensure single-bunch off-axis top-up injection affecting only 10 to 20 SR bunches that are 2 ns apart. The "Super-fast" one should bring the perturbed bunches down to only one. In "on-axis" mode it should be able to inject a top-up bunch between two SR bunches with minimum disturbance of the adjacent ones. To do this a combination of special beam injection schemes and an extremely fast (ns) kicker system is required. We will discuss the status of the development, the problems and the solutions for reaching such a challenging goal.

INTRODUCTION

Efficient injection into the SLS 2.0 SR is a challenge. Due to the strong nonlinearity of multi-bend achromat lattice the available dynamic aperture is two or three times smaller than the one of the existing SLS SR. The physical aperture as well is limited by small aperture insertion devices. Different strategies, like very thin injection septum and reduced booster ring emittance [1] etc. are planned to achieve stable and efficient injection in the new ring using the conventional 4-kicker bump.

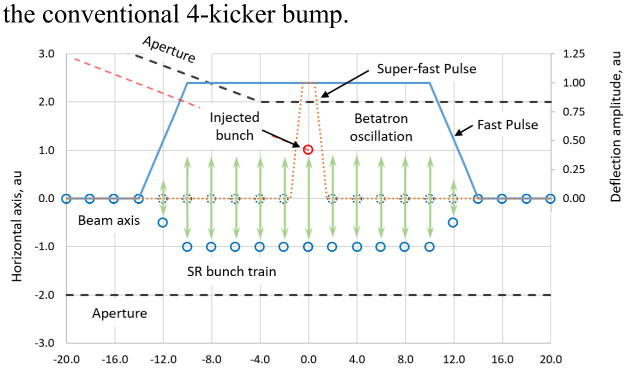

Figure 1: Simplified representation of "Fast" and "Super-fast" injection in "aperture sharing" mode.

Along with this, two advanced injection schemes are under development in order to ensure even more "transparent" top-up injection. The first one is called "Fast injection" and will utilize "aperture sharing" injection mode. There, injected and stored beams are deflected simultaneously by a short pulse kicker, in such way that they both stay within the ring aperture. The number of stored bunches deflected by the kicker is proportional to the pulse length (Fig. 1, blue waveform). The injection process can be quasi-transparent to the photon beam users when short deflection pulse is used and only limited number bunches are disturbed as it is shown in Fig. 1. The second, called "Super-fast" injection should follow. There, a deflecting pulse shorter than twice the bunch spacing (Fig. 1, orange dashed line), will affect only one SR bunch, bringing the number of disturbed bunches to the ultimate minimum for "aperture sharing" ("off-axis") injection mode. If the deflecting pulse is shorter than one bunch spacing (Fig. 2) an "on-axis" injection could be realized. In this mode the injected bunch is positioned on the SR beam axis and joins one of the adjacent SR bunch through damped synchrotron oscillation, avoiding any transvers beam disturbance [2].

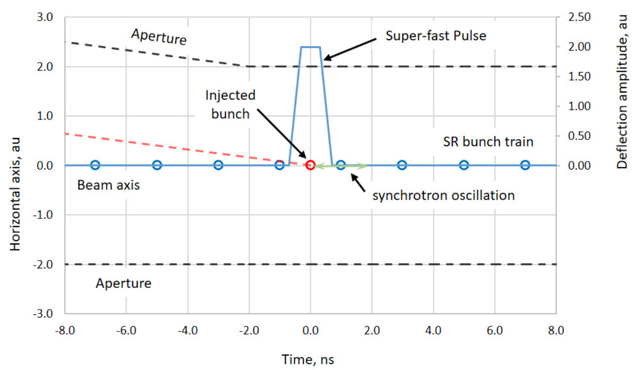

Figure 2: Simplified representation of "on-axis" injection mode with "Super-fast" scheme.

This motivates a development of kicker systems capable of nanosecond long deflection. To achieve this, two main components are needed: strong enough kicker capable of producing very short deflection times and reliable short pulse generator to power the kicker.

KICKER REQUIREMENTS

The idea of using fast kicker for injection, extraction, tail clipping etc. is not new [3-9]. For sufficiently large deflections, pulse amplitudes of tens of kilovolts are needed, and this high voltage gives considerable difficulty for reliable operation. Experiments were done with excitation pulses as high as couple of tens of kV but these amplitudes were not practical for reliable machine operation [3]. In order to make a more viable fast kicker system we used the following design strategies:

Moderate excitation voltage Limit excitation to ±4 kV (±9 kV) where more reliable and affordable pulse generators exist. As well, at these pulse amplitudes, it is possible to have broad bandwidth attenuators and the shape

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of the excitation pulse could be directly observed with fast oscilloscope. Well-matched loads will ensure that the beam-induced pulses in the kicker are well absorbed too.

Composite kicker design Use multiple short stripline kicker sections to achieve small deflection duration and to reach the required deflection strength.

Small kicker aperture The TEM kicker deflection depends on the electric/magnetic field strength (not to the absolute excitation voltage or current). With general reduction of the beam aperture, it is possible to reduce the distance between kicker blades and to reach moderate electric fields with lower excitation voltages.

The latter strategy was crucial for making such project feasible.

To make the system design efficient, we decided to design a kicker that meets the requirements for both, "Fast" and "Super-fast" injection schemes. Clearly, the design challenges come from the "Super-fast" one.

Table 1 summarizes the given parameters for the two injection schemes and Table 2 the derived and chosen ones.

Table 1: Given and Machine Related Parameters

Parameter	Fast	Super-fast
Beam momentum	2.7 GeV/c	
SR bunch spacing	2 ns	
Injection repetition rate	3 Hz	
Injection type	Horizontal	
Nr of defl. SR bunches[1]	<15	1
Nr of defl. SR bunches[2]	NA	0
Deflection angle[1]	>0.35 mrad	
Deflection angle[2]	NA	1.0 mrad
Horizontal aperture on axis	±5 mm	
Active kicker length	800 mm	

[1] Aperture sharing mode (off-axis)
[2] On-axis mode
NA – Not Applicable

Table 2: Derived and Chosen Kicker System Parameters

Parameter	Fast	Super-fast
Deflection type	Electromagnetic (TEM)	
Kicker type	Stripline (vacuum)	
Kicker section length	100 mm	
Number of sections	8	
Maximum deflection	0.5 mrad	1.0 mrad
Magnetic field	2.8 mT	5.7 mT
Electric field	0.9 MV/m	1.7 MV/m
Electrode voltage	±4.3 kV	±8.5 kV
Electrode current	±85 A	±170 A
Excitation pulse length	<30 ns	~1 ns
Odd / Even el. impedance	2x 50.0 Ω / 2x 56.0 Ω	

KICKER DESIGN

To have short deflection duration a vacuum stripline (TEM) kicker is chosen. When excited downstream the magnetic and electric deflection forces are in the same direction and for highly relativistic beams are roughly equal in magnitude.

Active Length

Each kicker section should meet the following two constraints, assuming bunch length is much shorter than the kicker electrical length:

Use efficiently kicker's length To have maximum deflection the excitation pulse should be long enough to "fill" the entire kicker "visible" to the electron bunch. Assuming perfectly rectangular excitation pulse ($t_r = t_f = 0$) with duration t_p the full amplitude deflection time (in the moving electron beam frame) could be expressed as following:

$$t_{100\%} = t_p - 2t_{el} \quad \text{for} \quad t_p > 2t_{el} \qquad (1)$$

where t_{el} is the electrical length of the kicker (wave propagation speed is equal to the speed of light).

Short deflection duration Some partial deflection will exist when the kicker is not fully energized so the total duration of non-zero deflection (in the moving electron beam frame) could be expressed as following, taking in account the finite pulse rise and fall times t_r and t_f:

$$t_{0\%} = 2t_{el} + t_p + t_r + t_f. \qquad (2)$$

Having in mind that SLS 2.0 SR RF frequency is 500 MHz, in order not to disturb the adjacent pulses in on-axis injection mode $t_{0\%}$ should be shorter than 2 ns. Assuming some practical rise and fall time limitations ($t_r = t_f = 0.4$ ns) for large amplitude pulses we can derive kicker section electrical length $t_{el} = 0.3$ ns. Respectively the full amplitude pulse duration should be $t_p < 0.6$ ns. For the practical design the kicker section is chosen to be close to the above calculated value – 100 mm.

Stripline Geometry

The kicker electrodes were optimized to produce the necessary field and electrical impedance maximizing the clear aperture on axis.

Figure 3 shows the cross section of the kicker blades. The small crescent-shape groove in the middle provides more distance to the beam on axis. Care was taken to avoid excessive surface electric field.

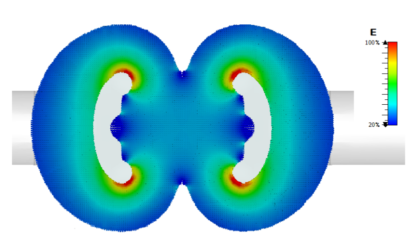

Figure 3: Kicker blades cross section with indicated relative surface electric field.

To propagate short electrical pulses without reflections the kicker's odd impedance (differential mode) should be very well matched to the feeding and terminating impedance (50 Ω). From the other hand good matching of its

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even impedance (common mode) will help extracting energy from the beam induced higher order modes minimizing the unwanted resonances and reducing the beam impedances. Due to topological reasons even impedance is always higher than to odd one. An engineering compromise targeted perfect fast pulses matching of the odd impedance and minimum deviation for the even one. Figure 4 shows both impedances using numerically simulated Time Domain Reflectometry (TDR).

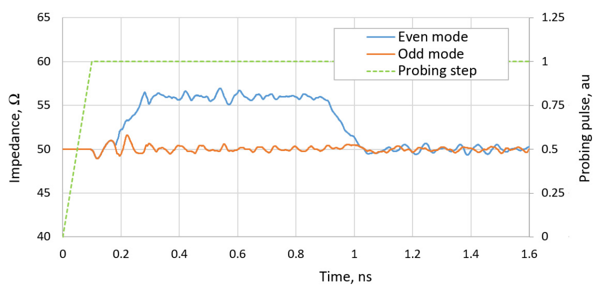

Figure 4: Even and odd mode TDR of one kicker section, probing step rise time 100 ps simulated with CST Microwave Studio®.

The kicker geometry is carefully optimized to introduce minimum unwanted beam impedances as well. Figure 5 shows the longitudinal beam impedance of one kicker section. The wake loss factor is 0.11 V/pC.

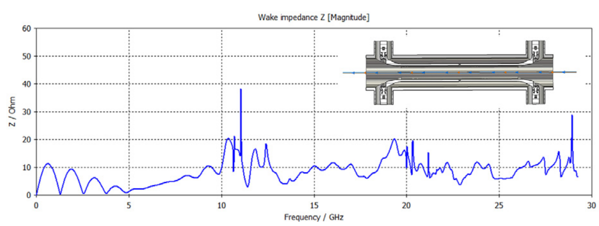

Figure 5: Longitudinal beam impedance of single kicker section simulated with CST Microwave Studio®.

SHORT PULSE GENERATION

Generation of short (nanosecond) electrical pulses with the required amplitude (couple of kV) is technically challenging and contribute as well to the project risk. In order to mitigate it and to optimize cost, the “Fast” injection pulse generator should be develop in-house and the “Super-fast” one should be acquired from an external company.

“Fast” Pulse Generator

With the introduction of the wide band-gap semiconductors like SiC the switching voltages of commercially available fast solid state switches extended to a couple of kVs. This opened new possibilities to their high power applications for switching tens of hundreds volts in tens of ns. In the recent years, GaN based FETs added the High Electron Mobility Transistors (HEMT) technology to the benefits of the wide band-gap semiconductors, providing for even faster switching speeds. The smaller required gate charge together with the HEMT effect made possible the switching times to be reduced down to single-digit nanoseconds. The ability of these devices to provide controlled turn on- and off-function allows a simpler design of pulse generators with fully controllable (short) pulse duration.

A low stray inductance Marx type generator is designed to produce 20-30 ns 5 kV pulses necessary for the “Fast” injection scheme. Figure 6 shows the output waveform of 5-stage prototype generator demonstrating the fast rise and fall capability of the GaN JFET based design.

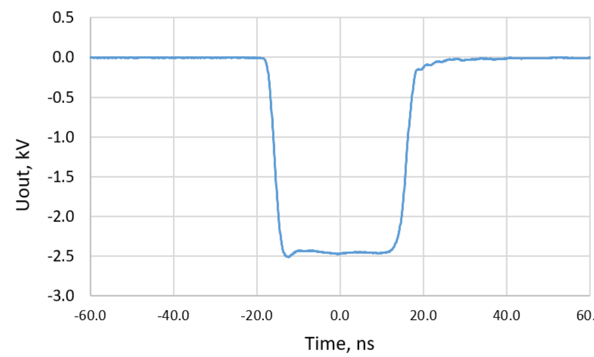

Figure 6: Output pulse waveform of 5-stage prototype GaN JFET based Marx generator.

We hope to have the full 10-stage version completed in the near future.

“Super-fast” Pulse Generator

For on-axis injection to utilize the ultimate speed of the kicker it has to be driven with a ±8.5 kV 1.5 ns pulse. A ±10 kV positive-negative prototype pulse generator pair was acquired from FID GmbH. Figure 7 shows the differential voltage waveform and the numerically calculated deflection pulse. The red circles represent the timing of the SR bunches and the green one – the injected bunch. As it could be seen the disturbance of the adjacent bunches is less than the set 30% limit (dashed line).

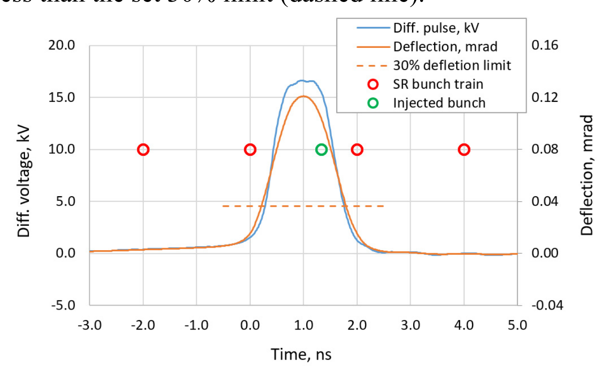

Figure 7: Differential voltage pulse waveform of FID GmbH pulse generator and the numerically calculated one kicker section deflection (in electron bunch frame).

CONCLUSION

The development of the SLS 2.0 advanced “Fast” and “Super-fast” injection schemes is challenging and is still associated with significant risk. Despite the technical difficulties the project is advancing and no uncircumventable obstacles have been identified.

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