KICKERS FOR INJECTION AND EXTRACTION IN DAMPING, COMBINER AND STORAGE RINGS

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Abstract

Injection and extraction kickers play a fundamental role in all the projects of new major accelerators at present under study. The feasibility of these accelerators depends also on the possibility to realize kickers based on unconventional design and new technologies. This paper describes the R&D carried out at LNF on two different types of deflecting devices. The first are the kickers for the Damping Ring (DR) of the International Linear Collider (ILC) and the Storage Rings (SR) of colliders like DAFNE. They require very low impedance, good field uniformity in a wide region around the beam axis and very short pulse duration for limiting the length and consequently the cost of the DR and for reducing the perturbation of the stored bunches in SRs. The tests made on stripline prototypes, fast high voltage pulsers and vacuum feedthroughs are presented. The second are the RF kickers for the CLIC Test Facility 3 (CTF3) for which an original SW structure has been designed and realized for the Delay Loop (DL) while a more conventional TW deflector allows the multiplication of bunch current and frequency in the Combiner Ring (CR). Results of their performances are described.

INTRODUCTION

An activity concerning the study, the design and the realization of devices for deflecting the trajectory of beams that must be extracted and/or injected in circular machines has been recently carried out at LNF.

The devices developed are different for typology and application and the motivations of the different choices are described in the following sections.

RF deflectors has been chosen in the two rings used for the bunch frequency multiplication in CTF3 [1][2]. In particular the RF deflector of the CR is a 10+2 cells TW structure operating in the TM_{11}, $2/3\pi$ mode [3][4], while the deflector for the DL is a system composed of a hybrid junction (HJ) coupler and two SW cavities which resonate in the TM_{110} deflecting mode [5][6]. The main differences between TW and SW RF deflectors are reported in Table I. All this characteristics are consequence of the different bandwidth between the two types of devices.

The possibility of using TW RF deflectors also for the DR of the ILC [7] has been investigated [8][9]. To get significant factors of bunch recombination in the DR, which means significant reduction of the DR circumference, groups of deflectors powered in multi-frequency mode are necessary.

However, an alternative solution looks now possible thanks to recent developments of new technologies in the field of high voltage (HV) pulse generators. The characteristics of the pulse (amplitude up to tens of kV, rise time from 100 ps to 1ns, pulse width from 5 ns to 50ns and repetition frequency up to hundreds of kHz) seem promising for the use of these fast pulsers to feed the kickers in the DR, where the bunch spacing must be strongly reduced.

Table 1: Comparison between TW and SW RF deflectors

main features	SW	TW
efficiency per unit length (deflection vs RF power)	high	low
filling time	proportional to the quality factor: generally slow.	~ to the group velocity and structure length: generally fast
deflecting field vs. n (# of cells)	scales as $\sqrt{n}$	scales as $n\left(1 - e^{-\alpha_l}\right)$ with α=attenuation
maximum number of cells	the maximum number of cells is limited because of mode overlapping	in principle there are no limitations to the number of cells.
temperature sensitivity	automatic tuning system or precise temperature stabilization	less temperature sensitivity.

People from several different laboratories are working on the design of stripline electrode kickers or on development of fast HV pulsers [10].

At LNF we have studied this solution for the upgrade of the DAFNE injection system. A special stripline kicker has been designed and its realization is in progress[11]. This activity is also a valid R&D of the injection and extraction kicker for the ILC Damping Ring.

THE CTF3 DELAY LOOP DEFLECTOR

The RF deflector allows the bunch frequency doubling process that takes place in the DL. Referring to the scheme illustrated in Fig. 1, the beam coming from linac is composed of an alternate sequence of so called even
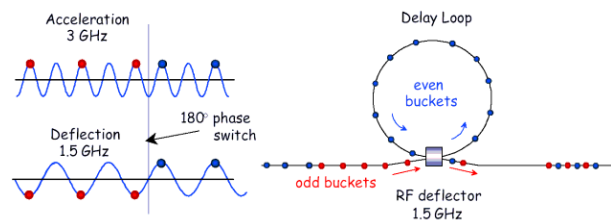

Figure 1: The bunch frequency multiplication scheme in the CTF3 Delay Loop.

and odd trains, which differ for a 180° phase jump between each other. This sequence of 140ns long sub-trains is realized by a pre-bunching system. The RF deflector gives kicks of the same amplitude but opposite

sign to the incoming even and odd trains. Only the even trains are injected into the ring and, after a turn, they are extracted and interleave with the following odd train.

The RF deflector system deflects of ±15mrad beams with energy up to 300MeV. The total train length is 1.4µs and the deflection given to the bunches is uniform within 1%. Peak power and duration of the RF pulses feeding the RF deflector are 20MW and 5µs respectively.

The deflector has been conceived as two cavities fed by the same klystron through a 90° hybrid junction (see Fig 2).

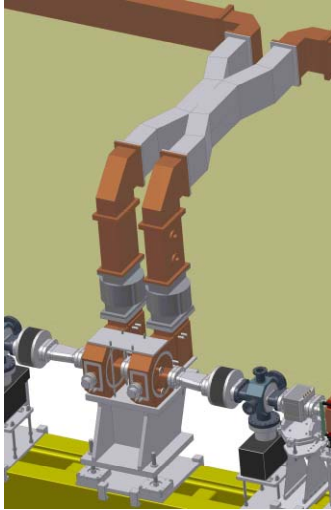
Figure 2: CAD drawing of the Delay Loop region with the RF deflector system.

Being the cavities $(1+1/4)\lambda_{RF}$ apart along the beam trajectory, where λ_{RF} is the free space wavelength at the RF frequency (1.499275GHz), the beam takes the same deflection in the two gaps. The Q is determined by proper dimensioning of the input coupler and the chosen value results from a compromise between the needs to have enough shunt impedance and sufficiently fast rise time as response to the RF pulse. Fig.3 shows the time domain signal monitored from one cavity when the 5 µs RF pulse is applied. The drop of the deflecting voltage in the last 1.4µs of the pulse, i.e. the spread of the kick amplitude along the train length is limited at less than 1%.
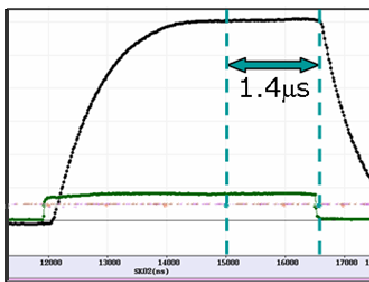

Figure 3: Cavity voltage vs. time with 5ns input pulse.

As it is shown in Fig. 4, the cavities reflect back the incident power both during the transients (the resonance has finite bandwidth) and the flat-top of the pulse (the input coupling coefficient is β≠1). However the HJ isolates the klystron from this reflected power, while it is dissipated in the load.
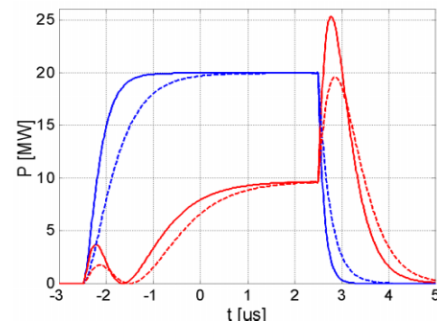

Figure 4: Time domain cavity response to a step input (Blue – RF input pulse. Red – cavity reflected power).

The klystron could be protected by a ferrite circulator as well, but the solution adopted presents two main advantages: the shunt impedance of the deflector is doubled by the use of two cavities and an expensive component like the circulator is avoided.

The deflector has been successfully used during the DL commissioning [12]. The train recombination was soon obtained and then improved in a few weeks of operation. Fig. 5 illustrates the results of recombination procedure. The beam current, equally distributed along the ten incoming sub-trains, results almost doubled where the trains are recombined and near to zero elsewhere.
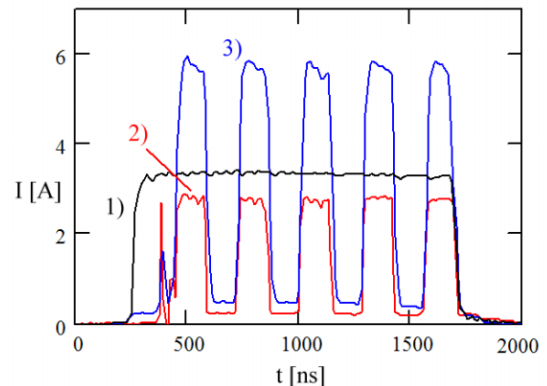

Figure 5: Beam current in the transfer line before the DL (black), in the DL (red) and after recombination (blue).

The deflector has been used also as a diagnostic device to measure the bunch length [13]: if the RF phase is 90 degrees shifted respect to normal condition of operation, the bunches cross the cavities when the field amplitude is zero and time derivative is maximum. The particles receive different transverse kicks, depending on their longitudinal position in the bunch. The streak camera measurement of the beam profile downstream the RF deflector gives direct information of the bunch longitudinal length before the kick.

THE COMBINER RING DEFLECTOR

In the DL take place the first stage compression by a factor of two of the bunch train. The CR is used in the second stage to further compress the pulse by a factor of five according to the scheme described in Fig 6. The bunches coming from the linac are on the crest of the deflector RF wave and take the kick to be injected in the

CR. The ring circumference differs for 1/5 respect to a multiple integer of the RF wavelength, so that in the following turns the already injected bunches pass in the RF deflector out of the phase of maximum field and their trajectory remains below the septa magnet. A second deflector has the function to compensate the residual kicks that the first one gives to the stored bunches.
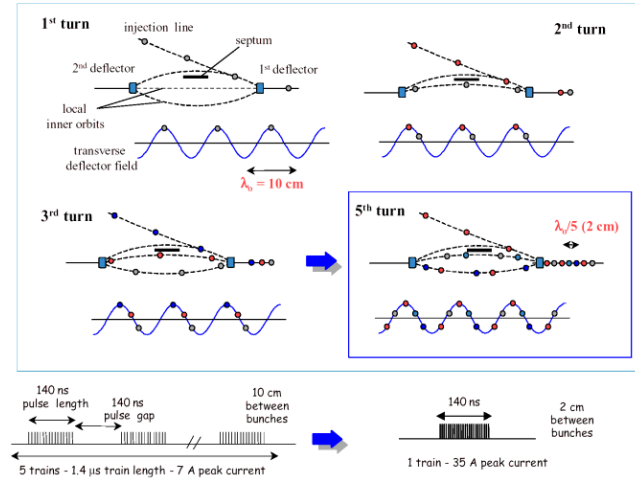

Figure 6: Bunch frequency multiplication in the CR.

The two RF deflectors working at 2.99855 GHz has been only just installed in the CR but they are already successfully tested in the CTF3 Preliminary Phase, a low current test of the bunch train combination in the EPA ring of the former LEP Pre-Injector (LPI) complex at CERN. The deflector parameters are reported in Table II.

Table 2: Combiner Ring RF Deflector Parameters

Frequency (f)	2.99855 [GHz]
Cell length (D)	33.33 [mm]
Cell radius (b)	56.01 [mm]
Iris internal radius (a)	21.43 [mm]
Iris thickness (t)	9.53 [mm]
Number of active cells (N_c)	10
Phase advance per cell (βD)	$2\pi/3$
Deflector length (L)	33 [cm]
Group velocity (v_g/c)	-0.0237
Filling time (τ_F)	47 [ns]
Shunt impedance per unit length (r_s)	18.1 [MΩ/m]
r_s/Q	1425 Ω/m
Input power (P_{in})	2 MW
Deflection (ϕ_D)	5 [mrad]

The design of the deflector has been done scaling to the CTF3 working frequency the dimensions of CERN RF separators (the so-called *Langeler structures*). These are disk-loaded backward waveguides working in the $2\pi/3$ EH_{11} hybrid mode already optimized for beam deflection [14][15]. The final 10 cells structure is shown in Fig. 7.

With 2D simulations the dimensions of each cell have been optimized. The $2\pi/3$ EH_{11} mode dipole degeneration of the two orthogonal polarities, has been removed by

inserting 2 longitudinal rods crossing off-axis the cells (just like the CERN separators).

The structure has been characterized by simulating and measuring the dispersion curves of a stack of 8 cells (+2 half cells). Finally the coupler has been designed with the 3D code HFSS [16] and the reflection coefficient (S_{11}) at the device input port has been minimized. Measured dispersion curve and S_{11} fulfil design requirements.
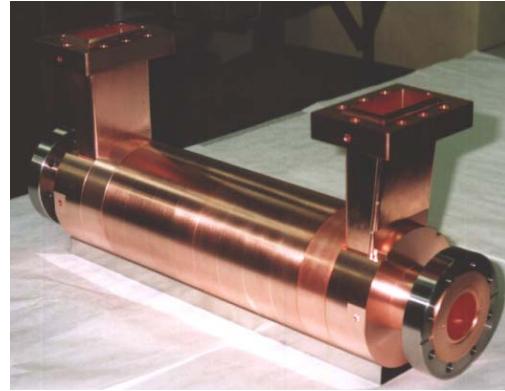

Figure 7: Picture of the CR deflector.

The deflectors have been made on OHFC high quality copper using hard soldering (brazing) technique. For simplifying the fabrication it has been decided to avoid a tuning system of the cells. The correct frequency and field phase advance has been obtained by performing different sets of measurements on prototypes and by carefully controlling the machining and soldering procedure.

The streak camera images of Fig. 8 show the results of the recombination process obtained during the CTF3 Preliminary Phase runs.
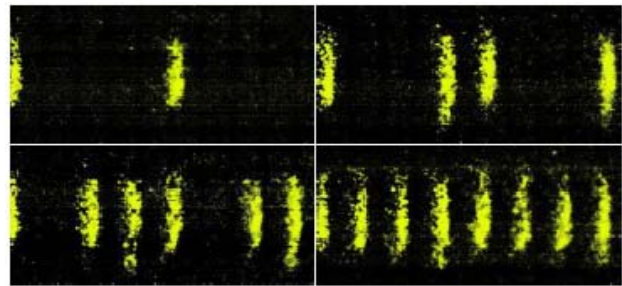

Figure 8: Bunch train combination of factor four, as observed with a streak camera. The images are taken for one to four bunch trains injected.

RF DEFLECTOR IN MULTIFREQUENCY MODE FOR THE ILC DAMPING RING

The scheme adopted for the CTF3 CR could be a good solution for the bunch injection and the extraction in the DR of ILC. The separation between the bunches in the linac should be strongly reduced in the DR unless to have a huge circumference of the ring. The original distance has to be restored between the bunches leaving the DR. Referring to Fig. 6, the injection process occurs as described for the CTF3 CR, while in the phase of extraction the two deflectors invert their roles. The second one kicks the beam for the extraction and the first corrects the orbit of the bunches not yet extracted.

As an example, to limit the CR circumference below 15km, the compression factor (F) should be at least F=20, which means to put at least 20 bunches in a period of the RF sinusoid, as represented in Fig. 9. But, for a given amplitude of the RF deflecting voltage, the difference (Δφ∗) between the deflection angle given to the injected or extracted bunch respect to the adjacent bunches becomes as smaller as F increases. If Δφ∗ is too small it is difficult to discriminate the bunches that have to pass above or below the septa magnets. An obvious solution to increase Δφ∗ consists in increasing the amplitude of the deflecting RF and this can be done with the use of a large number of deflectors in each of the two groups used for the injection or for the extraction.
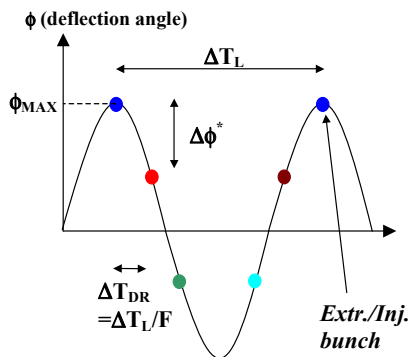

Figure 9: Bunch distribution over the RF voltage.

Alternatively, just two or three deflectors for each group are sufficient if they are powered with RF frequencies slightly different. With an optimal choice of these frequencies the ratio Δφ∗/φ$_{MAX}$ can be significaticively increased. Fig. 10 shows the situation for the case of 3 different frequencies and F=20.
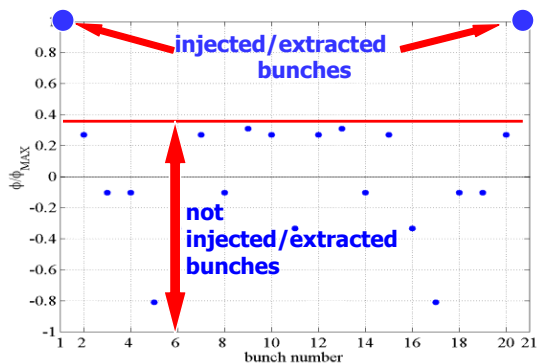

Figure 10: Deflection with 3 frequencies and F=20.

THE FAST PULSE KICKER FOR ILC DAMPING RING AND DAFNE

Recent developments of new technologies have made realistic the hypothesis of using fast HV pulse generators to feed kickers capable to give transverse momentum to the bunch injected in a ring without perturbing the orbit of the adjacent ones. With a kicker pulse duration sufficiently fast the bunch distance in the ring and therefore the ring circumference can be reasonably short. Groups from different laboratories are working on R&D

programs concerning both fast pulser development and kicker design.

The injection and extraction kickers for the positron DR, which has a minimum bunch distance of 6.2 ns, should satisfy the following requirements:

− Ultra short rise and fall time (total pulse duration<12ns);
− High integrated strength;
− deflecting field uniformity within few percent over 90% of the beam stay clear;
− impedance of the structure as low as possible;
− 3MHz repetition rate.

The same fast pulse technology and similar kicker requirements are needed for the upgrade of the DAFNE injection system. Once installed in DAFNE, these new kickers will be an important test for the ILC project, since they should demonstrate, with beam measurements, the achievement of the kicker performances. These kickers could also be used to test new fast pulsers produced by different laboratories or industries. Compared to the present DAFNE injection kickers [17] the new ones have the following characterisics:

− much shorter pulse (≈ 12 ns instead of ≈ 150 ns);
− better uniformity of the deflecting field;
− lower impedance;
− higher injection rate (max 50 Hz).

The much shorter pulse allows perturbing only the injected bunch and the two adjacent ones while, at present, a large fraction of the stored bunches (50/110 with 2.7 ns bunch spacing) are affected by the injection kick. This improvement, by reducing the perturbation of the kicker injection pulse on the stored bunches, can increase the current threshold of the transverse instability in the positron ring (as it has already been observed experimentally at DAFNE). The better uniformity of the deflecting field can increase the injection efficiency at high currents and reduce the background to experiments during injection. The broadband impedance, according to the calculations, is reduced by a factor 3 with respect to the present kickers. Moreover, since the new kickers have been designed with the same beam pipe cross section of the dipoles, no tapers are needed between the dipoles and the kicker and this also contributes to the reduction of the machine impedance. Finally, the possibility of injection at 50 Hz can be useful for future upgrades of the whole injection system.

The kicker has been designed as a conventional device with stripline electrodes. The peculiarity is in a proper shaping of the striplines, which allows to:

− reduce the broadband beam impedance of the structure;
− improve the deflecting field uniformity as a function of the transverse coordinate (horizontal in particular);
− obtain a better matching between the generator and the kicker structure at high frequency.

The kicker structure is sketched in Fig. 11. Each transverse section has constant 50Ω characteristic impedance matching the output impedance of the high

voltage pulse generator. The deflecting field configuration on the transverse plane of the structure varies according to the stripline coverage angle. Narrow striplines have stronger field intensity close to the electrode while for larger stripline the maximum intensity is in the center of the structure. Optimizing the relative length of the tapers respect to the straight section of the stripline, this property has been used to get a uniform deflection within few percent along the transverse coordinates.
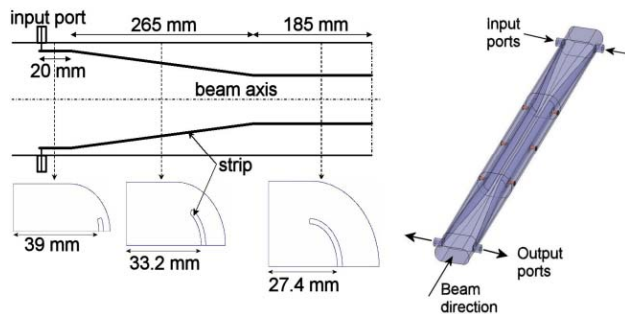

Figure 11: Sketch of the half kicker and HFSS 3D model.

The small dimensions of the stripline end sections assure well matched transition between the coaxial input/output lines and the stripline and reduce the longitudinal and transfer impedance of the structure. The longitudinal and transverse impedances have been calculated and Fig.12 shows the result obtained in the longitudinal case.
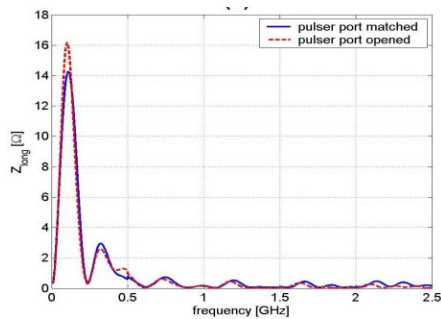

Fig. 12: Longitudinal beam impedance (HFSS simulation).

The needed deflecting voltage is obtained applying 45 kV to each electrode of the designed kicker. The German company FID GmbH [18] has developed a series of fast power generators which can produce trapezoidal voltage pulses with the characteristics needed for DAFNE (amplitude up to tens of kV, overall pulse width from 5 ns, no secondary pulses, pulse jitter limited to 20÷30ps). A 50 kV pulser has been commissioned to FID.

High voltage (HV) tests on prototypes are therefore necessary to verify if there are discharges on vacuum feedtrough, connectors or between the strip and the vacuum chamber. To this purpose a small prototype of the kicker has been constructed. The device has a uniform strip with the same section of the kicker stripline end section (the region with the higher field intensity). On the test device can be mounted different types of feedtroughs in order to perform measurements and tests on them and

to pick out a suitable one. First high voltage tests have been carried out with a 24 kV 7ns pulse generator courtesy given by FID GmbH. No discharges have been registered in the stripline test structure.

CONCLUSIONS

Different typologies of devices for injecting and extracting the beam in combiner or damping rings has been studied, designed and realized in the last years at LNF. An original RF deflector system and a TW RF deflector have been constructed for the CTF3 DL and CR respectively. Both of them have been already and successfully commissioned. The possibility to use TW structures powered in a multi-frequency mode has been investigated for the ILC DR. Finally a stripline electrode fast pulse kicker has been designed for the upgrade of the DAFNE injection system and it is now under construction. The same design criteria are valid to implement a fast kicker for the ILC DR.

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