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Cascading RF deflectors in compact beam spreader schemes

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ABSTRACT

This paper describes beam distribution schemes based on transverse electric field radio-frequency deflectors (RFD) as fast-switching devices and provides numerical relationships between their respective frequencies and phases. The adoption of compact transverse deflecting cavities represents an ideal solution for the design of high repetition rate (> 1 MHz), compact beam distribution systems. While directly applicable to modern FEL facilities, this approach also provides opportunities for expanding existing beam delivery systems with additional experimental areas simultaneously feeding multiple beamlines. We derive the formalism for cascading RFDs by adopting the proper choice of deflector frequencies which can generate a large variety of beam switch yard topologies. We present for reference a potential application operating at an rf frequency of 325 MHz with the comparison of three possible distinct compact rf deflectors: a superconducting rf-dipole, a normal conducting rf-dipole, and a normal conducting 4-rod design.

1. Introduction

Reduced amplitude initial horizontal deflections in a conventional beam switch yard (BSY)[2] involve long beam lines to provide clearance to the downstream deflecting and focusing elements. Options for the choice of a compact deflector are limited by technology considerations and stability requirements. Conventional electromagnetic kickers are limited in repetition rate by the maximum average power that the devices and the driving electronics can handle in order to assure the required pulse-to-pulse stability and repeatability. Moreover, the limited kick amplitudes associated to these structures involve important footprints for the devices and achieving the required compactness and mechanical stability becomes challenging in multi-GeV beam lines. The next option is to use transverse rf deflecting structures (RFD),[3] where conventional copper structure or superconducting radio-frequency (SRF)[4] solutions can be considered.

The adoption of the RFD technology offers some considerable advantages over stripline- and ferrite-based fast kickers options. It allows distributing electron bunches with on-demand repetition rates in each line, well above the few hundred kHz limit represented by fast kickers. In addition, the steady state nature of the cw transverse rf fields provides higher deflection stability and better shot-to-shot reproducibility as compared to those achievable with fast kickers where the deflecting pulses are created at every bunch passage.

Normal-conducting copper structures technology is well known and understood. These structures can provide high repetition rates, strong deflecting kicks in a limited footprint and represent a viable solution when thermal dissipation and average power considerations come to play.

The SRF technology provides in principle the most flexible solution, capable of supporting a potentially unlimited bunching rate. Although cavity production and processing, as well as the use of a cryogenic equipment, involve additional logistic and financial involvements for accelerators without an existing SRF infrastructure, we describe this option for sake of completeness and to offer a review of all the possible configurations adoptable in a compact switching scheme.

Transverse deflecting rf structures, originally proposed at SLAC [1] and CEBAF [2] as tools for beam separation, phase space diagnostics, and bunch length measurements [3,4], have subsequently found additional applications as fast switching devices in beam distribution systems for multiple beam lines layouts [5–7].

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[1] Currently at SLAC National Accelerator Laboratory.
[2] BSY: beam switch yard.
[3] RFD: radio-frequency deflector.
[4] SRF: superconducting radio-frequency.

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The proposed approach represents an ideal solution for the design of novel compact beam distribution systems. It adopts an initial splitting module where small amplitude vertical kicks provided by rf deflectors are combined with horizontal deflections provided by properly designed Lambertson-type septum magnets (LSM)[5] located at a short distance downstream. With this scheme the distance required to clear the LSM thin septa is substantially shorter than in the case of horizontal splitting, leading to important reductions in the longitudinal extent of the beam lines.

Numerical rules support a wide range of RFD cascading schemes. For sake of simplicity we limited this study to three-way splitting configurations with bunch passages on-crest and zero-crossing phases, and a two-way splitting with only on-crest passes, and their cascaded options. The analysis can be easily extended to schemes adopting kicks at phases between crest and zero crossing, as well as adding more cascaded stages.

Transport schemes such as the NGLS three-way spreader concept [8], or the LCLS-II beam switching and transport scheme [9] are examples of potential applications where rf deflectors could be adopted to achieve beam separation at very high repetition rate accelerators. The potential benefits of this approach are seen through the comparison among different compact RFD options, such as the three RFD compact cavity designs presented here for possible low frequency applications. These options include a superconducting rf-dipole (SCRFD)[6] cavity, a normal conducting rf-dipole (NCRFD)[7] cavity, and normal conducting 4-rod (NC4R)[8] cavity.

2. Natural beam splitting

2.1. Three-way split scheme

Following the scheme of Fig. 1, a cavity of frequency

$$f_1 = \left(\frac{n}{2} \pm \frac{1}{4}\right) R, \ (n \geq 1) \tag{1}$$

splits an incoming beam with uniform bunch rate R into three beamlets (*aliasing*) [10] with bunch rates:

$$R_1 = \frac{R}{4}, \text{ (two lines, on-crest passes) and} \tag{2}$$

$$R_2 = \frac{R}{2}, \text{ (central line, zero-crossing pass).} \tag{3}$$

The incoming rate R and the associated bucket separation are defined by the gun cavity frequency. The integer n helps tailoring the deflector cavity frequency to cope with competing requirements. Low frequencies (up to 400 MHz) are advised in order to mitigate side effects like emittance dilution from spatial chirp for bunches traveling at the zero-crossing phase [11], and to cope with timing and phase jitter tolerances. On the other side, higher n values provide more compact cavity/cryostat sizes and are beneficial to more compact layouts, when preserving beam quality is less important.

2.2. Two-way split scheme

When passes at the zero-crossing phase are not desired a two-way split scheme can be adopted where bunches are deflected on crest (Fig. 2). In analogy with Eq. (1) a frequency

$$f_2 = \left(n \pm \frac{1}{2}\right) R, \quad (n \geq 1) \tag{4}$$

will split the incoming bunch train into two beamlets each with rate $R/2$.

[5] LSM: Lambertson-type septum magnets.
[6] SCRFD: superconducting rf-dipole.
[7] NCRFD: normal conducting rf-dipole.
[8] NC4R: normal conducting 4-rod.

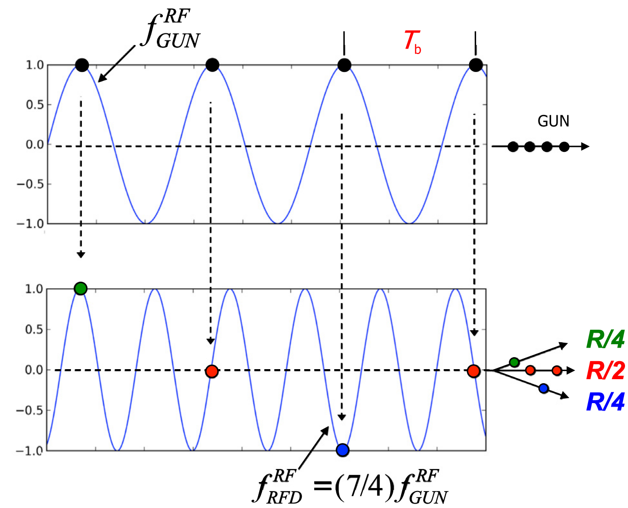

Fig. 1. Three-way splitting. A bunch train at repetition rate R reaches the RFD transverse field at phases corresponding to passes on-crest and at zero-crossing. Three beamlets emerge, two with rates $R_1 = R/4$ and one with rate $R_2 = R/2$.

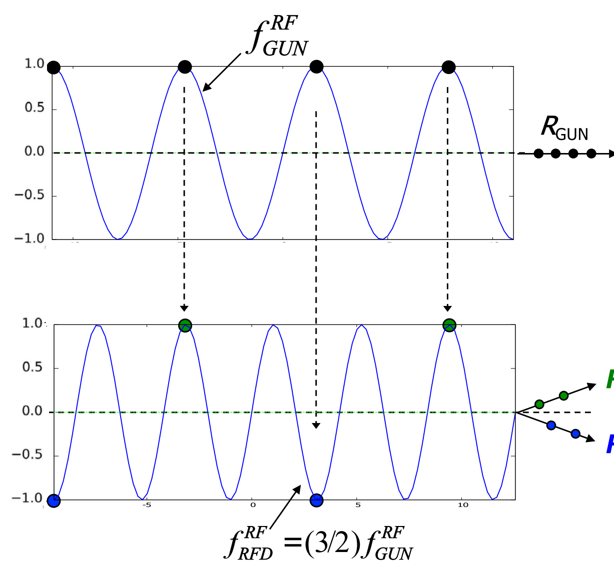

Fig. 2. Two-way splitting. A bunch train with repetition rate R reaches the RFD transverse electric field at on-crest phases producing two emerging beamlets with rates $R/2$.

3. Cascading RF deflectors

The outgoing beamline layout produced with this initial splitting procedure can be adopted for BSYs involving two or three end stations. More lines can be created by repeating the process after the first splitting, using a second bank of rf deflectors on each split line.

This cascading procedure can generate a variety of BSY topologies with a proper choice for the frequencies of the cascading rf deflectors provided that the proper rf frequencies are selected. In a three-way split scenario a frequency

$$f_3 = \left(\frac{n}{2} \pm \frac{1}{4}\right) R_1 = \left(\frac{n}{8} \pm \frac{1}{16}\right) R \tag{5}$$

will split each of the rates R_1 (Eq. (2)) into two lines at maximum rate $R/16$, and one at maximum rate $R/8$, for a total of six lines. The rate R_2 (Eq. (3)) is split into two lines at maximum rate $R/8$ and one at rate