AN RF DEFLECTING CAVITY BASED SPREADER FOR NEXT GENERATION LIGHT SOURCES*

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Abstract

The Lawrence Berkeley National Laboratory (LBNL) is developing design concepts for a multi-beamline soft X-ray FEL array powered by a superconducting linac with a bunch repetition rate of about one MHz [1]. A beam spreader will transport the electron beam to any FEL line with minimal beam loss at any operational energy and rate. This paper documents a novel system where the use of RF Deflectors (RFD) as fast-switching devices is proposed. The LBNL site-complying spreader scheme can be configured to fit any beam switchyard topology including an array of beamlines symmetrically split at both sides of the linac.

Introduction

Electron bunches supplied by a high-brightness, high-repetition-rate photocathode gun and accelerated in a CW linac to a nominal energy of 2.4-GeV are distributed by a beam spreader into an array of independently configurable FEL beam-lines with nominal bunch rates in the MHz range in each FEL.

Superconducting RF dipole cavities [2] provide vertical deflection for bunches traveling on the crest and at the zero-crossing of the transverse electric field in the cavities (three-way splitting). The emerging trajectories are horizontally bent by two Lambertson magnets and a standard horizontal dipole to create a three-branches takeoff section. The process, applied to each branch, produces the nine lines spreader layout of Figure 1.

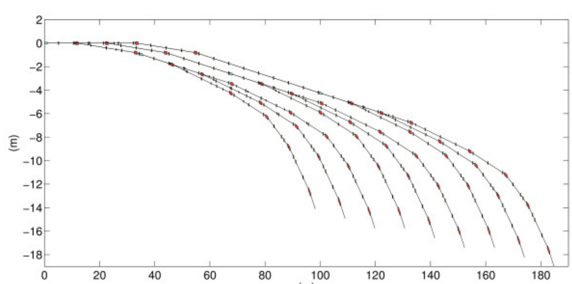

Figure 1 : The 9 FEL lines layout of the NGLS spreader.

The achromatic and isochronous transport lines preserve the beam qualities after a total 36-deg deflection, and provides a 5.56 / 6.23-m separation between the FEL lines within a compact footprint. The Gun-Spreader complex is suitable to deliver photon bunches with equal arrival time at detectors in adjacent lines (“Two-color” X-ray pulse capability) by populating RF buckets with time separation consistent with the beamlines path length.

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The Takeoff Section

A novel takeoff scheme evolved from the original one [3] is shown in Figure 2. Bunches arriving at the RFD1 dipole cavity are either vertically deflected by ±1.15-mrad (on crest passage) or travel straight (zero-crossing passage) while two Lambertson septa (LSM) and a conventional dipole (HB) provide horizontal deflections.

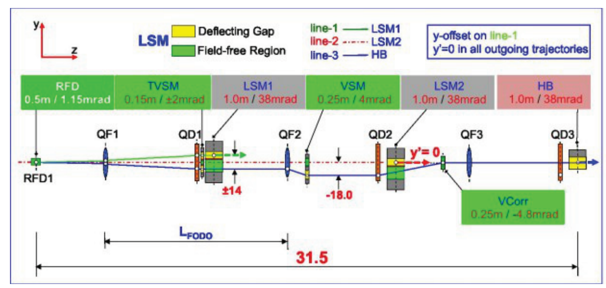

Figure 2 : The RFD takeoff section showing three vertically deflected trajectories horizontally right-bent by two Lambertson and one standard dipole.

The LSM1 Lambertson magnet provides a 38-mrad horizontal deflection to line-1 and transmits undeflected the line-2 and line-3 trajectories in the zero-field channel. The line-2 travels at the zero-crossing phase of the RF deflector and is deflected by the LSM2 septum while the line-3 is eventually deflected by the standard dipole HB. The Lambertson septa are both installed in upright position, differently from what suggested in [3], and are mechanically and magnetically identical. Their design features together with a Poisson’s modelization have been described in [3]. The Vertical Septum Magnets TVSM and VSM with the corrector VCorr provide individual vertical steering and slope control. The three split trajectories emerge with no vertical slope so their offsets remain contained and can be compensated anywhere downstream without requiring the use of large correctors. The deflecting elements are imbedded in a 10.87-m long cell, 90-degree phase advance FODO structure.

This module, repeated on each split branch with different orientations, can produce a variety of beam distribution schemes. In the NGLS configuration it generates the nine beamlines spreader scheme of Figure 1. The main takeoff parameters are collected in Table 1 of Ref. [3].

The RF Deflectors (RFD)

The adoption of transverse RF-deflectors allows for bunch repetition rates well above the ~150-kHz limit represented by stripline and ferrite fast kickers. Frequencies lower than 400-MHz are considered in order to limit emittance dilution from spatial chirp for bunches

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traveling at the zero-crossing phase [4]. The present RFD approach is based on recent progress [2] on SRF cavities developed at ODU and BNL for the LHC Luminosity Upgrade Crab System. Options for room temperature deflectors are also being considered [5] provided requirements on phase and amplitude stability can be met.
A preliminary design for a superconducting RF dipole cavity operating around 325.0 (a lower operating frequency around 139 MHz maybe needed to minimize phase jitter effect) is illustrated in Figure 3 where the transverse field longitudinal profile is for a horizontal deflection and a 70-mm beam aperture. A peak electric field ε_{y0}=7.45-MV/m and a θ_y=1.15-mrad deflection call for an integrated RF deflector length

$$L_{RF}^{eff} = 0.40\,m. \qquad (1)$$

A cavity with effective length equal to the λ/2 figures of the deflecting mode for the two frequencies provides the desired deflection.

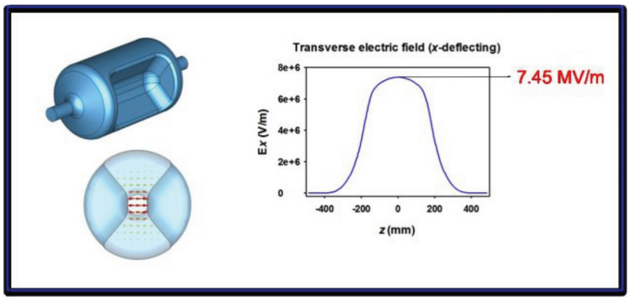

Figure 3 : The RFD cavity and the longitudinal profile of the transverse electric field (shown for horizontal deflection).

Gun Timing and Bunch Repetition Rates

The nine beam lines of the NGLS spreader can be filled with different bunch rates depending on the temporal structure of the bunch train generated at the RF Gun [6].
A ***uniform*** bunch repetition rate R is split into three sub-rates (aliasing) by a cavity RFD1running at frequency

$$f = R\left(\frac{n}{2} \pm \frac{1}{4}\right)(n \geq 1) \qquad (2)$$

The Gun cavity frequency sets the maximum bucket rate

$$R_{Gun} = 1300/7 = 185.71\text{-MHz}. \qquad (3)$$

From (2) a frequency f_I=325.0-MHz (n=3) divides the incoming rate (3) into three lines with sub-rates

$$R_1 = R_{Gun}/4 = 46.43\text{-MHz (two lines on crest)}$$
$$R_2 = R_{Gun}/2 = 92.86\text{-MHz (central line at zero-Xing)} \qquad (4)$$

This *natural splitting* situation is illustrated in Figure 4. Applying the process to a second bank of three deflectors will generate nine beamlines. From (2) a frequency f_2=(29/16)R_{Gun}=336.61-MHz would correctly split the rate R_1 as will a frequency f_3 =(30/16)R_{Gun}=348.21-MHz for the rate R_2. A scenario with RFD2 and RFD3 running at a frequency f_2 and RFD4 at a frequency f_3 will produce four lines at 11.61-MHz rate, four at 23.21-MHz rate and one at 46.43-MHz.

A selective filling of specific Gun RF buckets (missing bucket option [6]) produces an alternative scenario with three lines fed at the same rate R_1. Running the three RFDs at the frequency f_2 will then produce six lines at 11.61-MHz rate and three at 23.21-MHz.

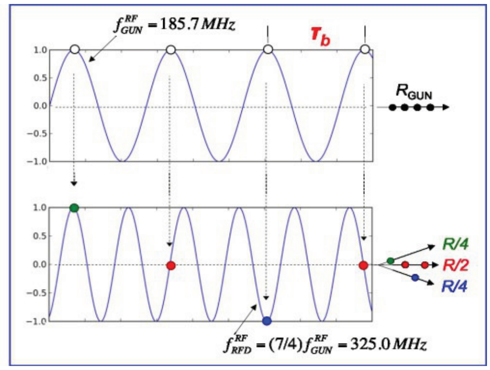

Figure 4 : Aliasing applied to the Gun and the RFD systems.

Tolerance Requirements

The use of RF deflectors involves a spatial chirp for bunches travelling at the zero-crossing phase [4]. The relative projected emittance growth is given by

$$\frac{\Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1+\left(\frac{2\pi x_0'\sigma_z}{\lambda}\right)^2 \frac{\beta\gamma}{\varepsilon_N}} - 1 \qquad (5)$$

where λ is the RF wavelength, σ the rms bunch length and x_0'=eV/E_0 the deflection at the crest. In addition to a spatial chirp, the bunch centroid may be kicked due to jitter in the bunch arrival time and/or in the cavity amplitude and phase. The rms phase jitter tolerance at the zero-crossing and the RF amplitude tolerance at the crest phase are expressed by

$$\sigma_{\Delta t} \leq \frac{n_\sigma}{2\pi\nu}\frac{E_0}{eV}\sqrt{\frac{\varepsilon_N}{\beta\gamma}} \quad , \quad \frac{\sigma_V}{V} \leq n_\sigma \frac{E_0}{eV}\sqrt{\frac{\varepsilon_N}{\beta\gamma}} \qquad (6)$$

where n_σ is the allowable rms centroid jitter in units of a fraction of the transverse rms beam size.
Lower frequencies and a weaker RF kick would minimize the emittance growth and reduce phase and amplitude jitter effects. With a 1.15-mrad deflection from a 139.3-MHz RF cavity and the above beamline optics a n_σ=5% beam jitter would produce a relative emittance growth is about 1.04% and tolerances of the phase and amplitude jitters of 146-fs and 1.3×10^{-4} respectively. We are investigating the use of a third harmonic cavity [5] to further alleviate these effects.

The Branch Beam Transport System

The beam transport system from the Linac to the FEL lines must be achromatic to avoid emittance exchange between longitudinal and transverse phase spaces and to avoid transverse beam position jitter from energy fluctuations. The transport lines must also be isochronous to avoid bunch lengthening and time-of-flight jitter due to

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energy fluctuations. The optics functions of a typical spreader line (SLS1) are shown in Figure 5.

Each line has a FODO cell structure, consisting of a takeoff module, two double-bend achromats (DBA) and a triple-bend achromat (TBA). Each LSM is paired to a dipole magnet with same bending angle to form the DBA. Vertical septa (TVSM and VSM) in the takeoff sections contain the vertical orbit offsets within 20-mm and separate the kicked orbits from the un-deflected one. Vertical correctors downstream the DBAs compensate vertical orbit offsets and dispersion. The triple-bend achromat (TBA) at the end of each line is isochronous. A mirror-symmetric structure with three identical dipoles provides a 27.3-degree bending in the TBA. The total bending angle of each beam line is 36-degrees.

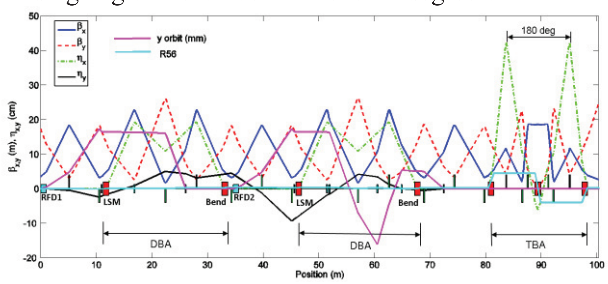

Figure 5 : Optics functions and vertical orbit offset of one typical spreader line (SLS1).

Two Colors Option

A "Two-color" X-ray option can be provided by the Gun-Spreader complex via a two-FEL synchronization with picosecond timing capability, achieved by populating Gun RF buckets selected consistently with the path length difference between specific beamlines. The synchronization condition requires the travel time difference along two beamlines of interest to be a multiple of the Gun bucket spacing $\tau_b=1/f_{GUN}=5.39$ns:

$$\Delta l / c = m\,\tau_b. \tag{7}$$

The path difference Δl includes the length, presently unknown, of the undulators in the beam lines, so the problem is initially restrained to that of transporting electron bunches with equal arrival time at a target line orthogonal to the beam-lines. From there the difference in the FEL lengths will have to be accounted for. Second order effects arising, for example, from the path length difference of electrons and photons in the undulators can be compensated by an adjustable chicane upstream the FEL in one of the electron lines.

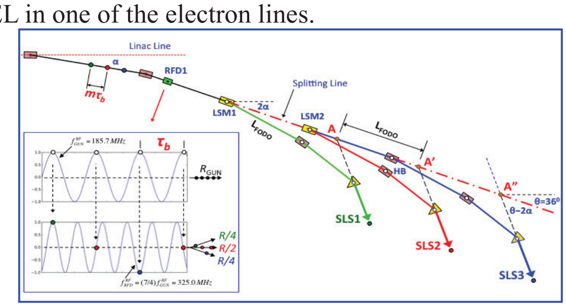

Figure 6 : Schematic of a 3-lines NGLS initial operation.

From the three-lines scheme of Figure 6, illustrating a possible NGLS initial operation, and the associated travel paths of Figure 7, where $l_1=AB$, $l_2=AC$ and $l_3=AD$, the two relationships

$$\begin{aligned} \Delta l &\equiv l_2 - l_1 = l_3 - l_2 = L_F[1-\cos(\theta-2\alpha)] \\ d &= L_F \sin(\theta - 2\alpha) \end{aligned} \tag{8}$$

show that the FODO cell length L_F and the separation d between two adjacent beamlines are linked by the time separation $m\tau_b$ between the Gun buckets to be illuminated:

$$L_F = \frac{m\,c\,\tau_b}{1-\cos(\theta-2\alpha)} = \frac{d}{\sin(\theta-2\alpha)} \tag{9}$$

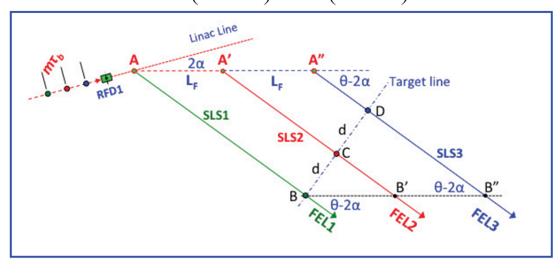

Figure 7 : Simplified optical scheme for a 3-lines option.

For our geometry (θ=36°, α=38-mrad) the choice $m=1$ (consecutive Gun buckets) implies a FODO cell length L_F=10.87-mand an FEL separation d=5.70-m.

Three consecutive bunches in the temporal order shown in Figure 4 will be traveling along the paths of Figure 7 and their travel times will match the path length difference in the three trajectories. With this choice two consecutive electron bunches traveling along lines SLS1 and SLS2 or SLS2 and SLS3 will be synchronous at the target line of Figure 7.

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