DESIGN CONCEPTS FOR AN RF DEFLECTING CAVITY-BASED SPREADER FOR A NEXT GENERATION FEL*

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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 spreader system, described in detail in [2], where the use of RF Deflectors (RFD) as fast-switching devices is proposed.

ELECTRON BEAM SPREADER CONCEPTS

Electron bunches supplied by a high-brightness, high-repetition-rate photocathode gun and accelerated in a CW linac to a maximum energy of ~2.4-GeV are delivered by a beam spreader to an array of independently configurable FEL beam-lines with nominal bunch rates up to one MHz in each FEL. Superconducting RF dipole cavities [3] operating at 325.0 and 336.6-MHz provide a three-way vertical deflection scheme for bunches traveling on the crest and at the zero-crossing of the transverse electric field in the cavities. The emerging trajectories are right-side bent by two Lambertson magnets and a standard horizontal dipole to create a three-split takeoff section. The process is repeated on each split branch to produce the nine lines scheme of Figure 1.

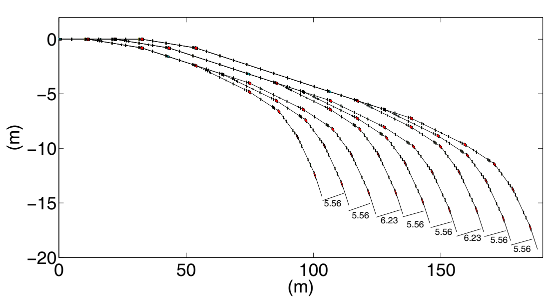

Figure 1: Schematic of the beam spreader system directing 1-MHz electron bunches from the Linac into 9 FEL lines.

A beam transport section providing achromatic and isochronous beam transport to the FELs follows each takeoff section. The beam-lines have a 36-deg total deflection to optimize beam optics properties within a reasonable footprint and provide a 5.65-m separation between the undulator lines. This scheme works for any beam switchyard topology including an array of beamlines symmetrically split at both sides of the linac.

The Takeoff Section

The takeoff scheme (elevation) is shown in Figure 2. Bunches arriving at the RFD1 deflector are either vertically deflected by ±1.15-mrad (on crest passage) or travel straight (zero-crossing passage). Two Lambertson septa (LSM) and a conventional dipole (HB) provide three 38-mrad right-deflections.

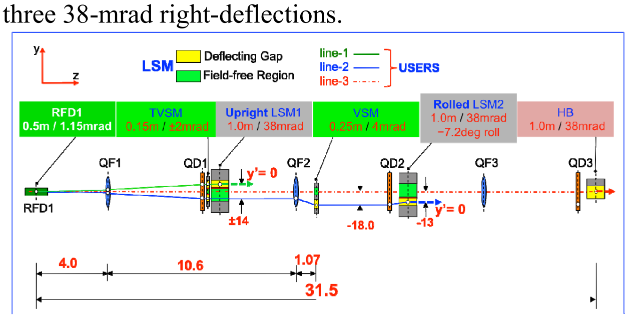

Figure 2: Elevation of the RFD takeoff section showing three vertically deflected trajectories horizontally right-bent by two Lambertson and one standard dipole.

The vertical slopes of the line-1 and line-2 outgoing trajectories are compensated to contain their vertical excursions, which are zeroed downstream without requiring the use of large correctors. The Twin Vertical Septum Magnet (TVSM) compensates the converging slopes from QD1 into the LSM1 which provides a 38-mrad right-side horizontal deflection to the beam entering the deflecting gap (line-1) and transmits undeflected the two trajectories (line-2 and line-3) in the zero-field channel. The Vertical Septum VSM steers line-2 into the deflecting gap of the LSM2 that also transmits the line-3 without deflection to the last bender (HB). The LSM2 is rolled around a longitudinal axis passing in the center of the zero-field region to compensate the slope of the ingoing line-2. The deflecting elements are imbedded in a 10.6-m and 90-degree phase advance/cell FODO structure adopting slim quadrupoles [4]. The main takeoff parameters are collected in Table 1.

The Lambertson Septum Magnets (LSM)

The eight Lambertson Septum Magnets provide a 38-mrad right-deflection and are mechanically and magnetically identical. The LSMs located immediately downstream the RFDs are installed in upright position, the downstream ones are rolled around the beam direction to add a small vertical deflection to compensate the slope of the incoming lines. Figure 3 shows a Poisson's rendition of the upright LSM.

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Table 1: Main Parameter List for the Takeoff Section

Parameter	Symbol	Unit	Value
Beam Energy	E	GeV	2.4
FODO Cell length	L_{FODO}	m	10.6
Cell Phase Advance	$\Delta\mu_{cell}$	deg	90
Quad Gradient	G	T/m	10.7
Quad Effective Length	L_Q	m	0.20
Quad bore diameter	d_Q	mm	60.0
RFD deflection	θ_{RFD}	mrad	1.15
RFD effective length	L_{RFD}	m	0.40
LSM and HB deflection	-	mrad	38.0
LSM and HB length	L_{LSM}	m	1.0
LSM2 roll	α	deg	-7.2
VSM deflection	θ_{VSM}	mrad	4.0
VSM length	L_{VSM}	m	0.25
TVSM deflection	θ_{TVSM}	mrad	±2.0
TVSM length	L_{TVSM}	m	0.15
Max. Vertical Traj. offset	-	mm	-20.0
Total Arc deflection	θ_{ARC}	deg	36.0
FEL lines separation	-	m	5.56

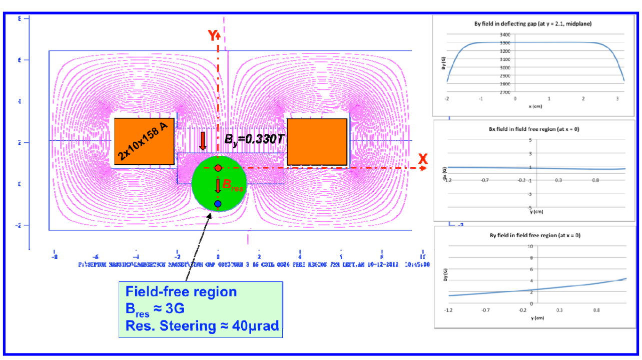

Figure 3: Poisson's model of the upright LSM.

The Vertical Septum Magnets

Differently from the Lambertson devices the Vertical Septum Magnets VSM and TVSM provide vertical deflections and are used to contain the excursion of the vertically offset trajectories separating them from the undeflected ones. In particular the Twin septa (TVSM) compensate the vertical slopes of the two trajectories ingoing the upright LSM in order to provide zero-slope outgoing trajectories and transmit un-deflected the bunches traveling at the RFD zero-crossing (Figure 1).

The RF Deflectors (RFD)

The adoption of transverse RF-deflectors allows for bunch repetition rates above the ~150-kHz limit represented by stripline and ferrite fast kickers. The envisaged frequencies are lower than 400-MHz to limit the emittance dilution from spatial chirp for bunches traveling at the zero-crossing [5].

Our RFD approach is based on recent progress [3] on SRF cavities developed at ODU and BNL for the LHC Luminosity Upgrade Crab System. Options for deflectors operating at room temperature are also being considered [6] if requirements on phase and amplitude stability can be met.

A preliminary design for a superconducting RF dipole cavity [3] operating at 325.0 and 336.6-MHz is illustrated in Figure 4. The transverse field longitudinal profile is for a horizontal deflection and a 70-mm beam aperture.

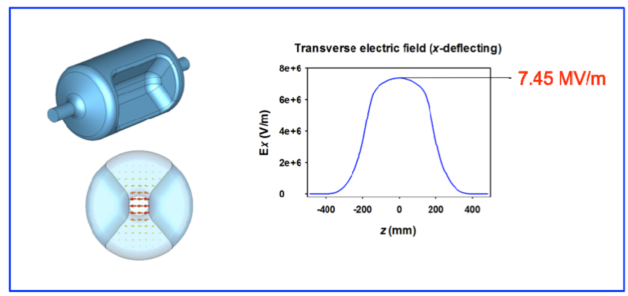

Figure 4: The RFD cavity and the longitudinal profile of the transverse electric field shown for horizontal deflection.

The vertical deflection experienced by the beam at the cavity traversal is

$$\theta_y \equiv \frac{\Delta p_y}{p_L} = \frac{1}{\beta E/e}\int_{L_c} \varepsilon_y \, dl = \frac{\varepsilon_{y0} L_{RF}^{eff}}{E_{beam}} \qquad (4)$$

where p_L ,Δp_y are the longitudinal and acquired transverse momenta and ε_y the transverse electric field. With a peak electric field ε_{y0}=7.45-MV/m (Figure 4) the required θ_y=1.15-mrad deflection at E_{beam}=2.6-GeV calls for an integrated RF deflector length

$$L_{RF}^{eff} = 0.40\,m \qquad (5)$$

and a cavity with effective length equal to the $\lambda/2$ figures of the deflecting mode for the two frequencies will provide the desired 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.

A ***uniform*** bunch repetition rate R can be split into three components (aliasing) by a cavity of frequency

$$f = R\left(\frac{n}{2} + \frac{1}{4}\right) \qquad (6)$$

The NGLS Gun cavity frequency sets the maximum Gun bucket rate:

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

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From (6) a frequency f_1=325.0-MHz (n=3) would divide the incoming rate (7) into three lines:

$R_1 = R_{Gun}$ /4=46.43-MHz (two lines on crest) and
$R_2 = R_{Gun}$ /2=92.86-MHz (central line , zero-crossing). (8)

This *natural splitting* situation is shown in Figure 5.

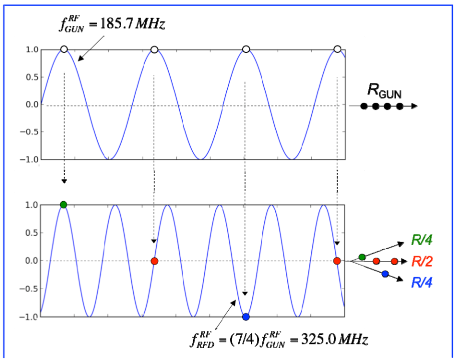

Figure 5: Aliasing applied to the Gun and RFD systems.

The three lines with repetition rates (8) reach a second bank of three deflectors to generate nine beamlines. A frequency f_2=(29/16)R_{Gun}=336.61-MHz will correctly split the rate R_1 but not R_2 for which a frequency f_3 =(30/16) R_{Gun}=348.21-MHz will work. A selective filling of specific gun RF buckets can produce three lines at rate R_1 (8) and the second bank of deflectors running at a frequency f_2 will produce six lines at 11.61-MHz rate and three at 23.21-MHz. An alternative 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.

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 energy fluctuations. The optics functions of a typical spreader line (SLS2) are shown in Fig. 6.

Each line consists of a takeoff module, a quadrupole matching section and a triple-bend achromat. In the takeoff section each LSM is paired to a dipole magnet with same bending angle. The 180-degree phase advance between the two magnets (two FODO cells) makes the dipole to cancel the horizontal dispersion generated by the LSM. 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 compensate orbit offsets and correct vertical dispersion. The second triple-bend achromat of each line is isochronous. A mirror-symmetric structure with three identical dipoles provides a 31.6-degree bending. The total bending angle of each beam line is 36-degrees.

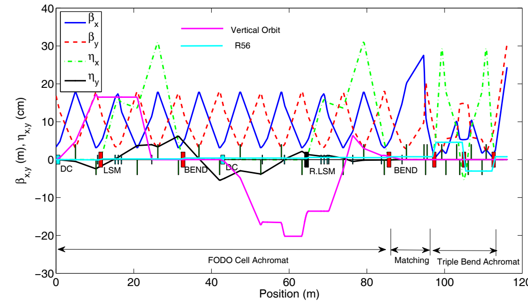

Figure 6: Optics functions and vertical orbit offset of one typical spreader line (SLS2).

Tolerance Requirements

Use of RF deflectors involves a spatial chirp for the bunches travelling at the zero-crossing [5]. The relative projected emittance growth is given by

$$\frac{\Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1+\left(\frac{2\pi x'_0\sigma_z}{\lambda}\right)^2 \frac{\beta\gamma}{\varepsilon_N}} - 1 \quad (9)$$

where λ is the RF wavelength, σ_z 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 also be kicked due to jitter of the cavity amplitude and phase. The rms phase jitter tolerance at the zero-crossing and the RF amplitude tolerance at the crest phase are given by

$$\sigma_{\Delta t} \le \frac{n_\sigma}{2\pi\nu}\frac{E_0}{eV}\sqrt{\frac{\varepsilon_N}{\beta\gamma}} \quad , \quad \frac{\sigma_V}{V} \le n_\sigma \frac{E_0}{eV}\sqrt{\frac{\varepsilon_N}{\beta\gamma}} \quad (10)$$

where n_σ is the allowable rms centroid jitter in terms of a fraction of the transverse rms beam size.

Lower frequencies and weaker RF kick would minimize the emittance growth and reduce phase and amplitude jitter effects. Using a 139.3-MHz cavity, a 1.15-mrad kick and the above beamline optics, the relative emittance growth is about 0.08% and tolerances of the phase and amplitude jitters are 64-fs and $6.5\text{x}10^{-6}$ respectively. We are investigating the use of a third harmonic cavity [6] to alleviate these effects.

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