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A COMPACT BEAM SPREADER USING RF DEFLECTING CAVITIES FOR THE LCLS-II*

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Abstract

The LCLS-II project currently under development is designed to accelerate electron bunches up to 4 GeV and transport them to one of two FEL undulators located more than 2 km downstream of the end of the LCLS-II linac. The upgrade requires a spreader system to separate the baseline electron bunches and transport them to two undulator lines or a local dump. Fast bipolar kickers (FK) or transverse electric rf deflectors (RFD) are considered as fast-switching devices (FSD). In the RFD approach described here three design options operating at 325 MHz are studied including a superconducting rf-dipole cavity, a normal conducting rf-dipole cavity, and a normal conducting 4-rod cavity. Optional compact splitting schemes involving a combination of vertical and horizontal initial deflections are addressed.

INTRODUCTION

The LCLS-II project will include a CW 4 GeV superconducting linac, with a nominal electron bunch output frequency of 1 MHz. In order to switch the beam to one of three destinations: the SXR undulator, the HXR undulator, or a beam dump, a stable and reliable high repetition rate beam spreader is needed. The conceptual design of the LCLS-II beam switching and transport scheme presented here is based on a modified version of the NGLS *three*-way spreader concept [1]. In this concept, an rf transverse deflector will provide a 1 mrad deflection to the electron bunch, in a vertical direction dependent on the phase between the electron bunch and the rf deflector. Three preliminary rf cavity design options, one superconducting (SC) and two normal conducting (NC), are presented for an operating frequency of 325 MHz. All simulations were done using CST Microwave Studio®.

COMPACT INITIAL SPLITTING MODULE

The deflections required to the FSD in a spreader scheme are of the order of 1mrad or less to comply with stability and reproducibility requirements. Schemes involving an initial splitting in the vertical direction further combined with horizontal deflections provided by properly designed Lambertson-type septum magnets (LSM) at a short distance downstream, offer options for substantial reductions in the longitudinal extent of the beamlines. As the LSM accepts contained vertical separations between the trajectories, the magnet can be installed at a relatively short distance from the FSD, resulting in more compact longitudinal footprint of the beam switch yard (BSY) layout. The basic scheme [2] for the splitting module is shown in Figure 1. The FSD vertically splits an incoming bunch train into three trajectories with a ±θ_F small amplitude angle. The initial slopes are enhanced by the vertically defocusing quadrupole Q1 and compensated at the entrance of the LSM downstream, which provides the first horizontal deflection.

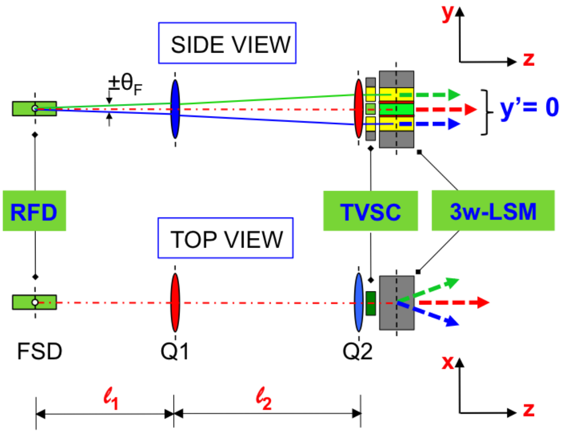

Figure 1: The initial splitting module. Three vertical trajectories are selectively deflected by a three-way LSM.

Vertical Splitting

The scheme essentially consists of a telescopic arrangement governed by the vertical matrix elements

$$R^{y}_{12} = \ y/\ _{F}\ ,\ R^{y}_{22} = 0\ . \qquad (1)$$

The separation Δy between the trajectories is defined by the position of Q_2 which also compensates the slopes at the LSM. A Twin Vertical Septum Corrector (TVSC) [2] can accomplish the slope compensation if Q_1 and Q_2 are part of a FODO cell. Solving (1) with the condition

$$l_1 + l_2 = \min \qquad (2)$$

gives, in thin lens approximation:

$$l_{1,2}\quad l = \ f_1 + \sqrt{f_1(f_1 + R^{y}_{12})}\ \ ,\quad f_2 = l\ \frac{2f_1 + l}{f_1 + l}\div \qquad (3)$$

where f_1 and f_2 are the focal lengths.

A numerical example for $R^{y}_{12} = 15.0$ mm/mrad and a conservative f_1=1.48 m gives l=3.46 m and f_2=4.34 m.

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Horizontal Deflection

Lambertson Septum Magnets (LSM) provide the first horizontal deflections. In a typical two-way LSM configuration a 2 mm thin septum separates the deflecting gap from the field-free region. A design of an “asymmetric” three-way LSM has been carried on in view of a possible use for LCLS-II. It produces up to 5- and 10-mrad opposite deflections at 4 GeV beam energy with a 0.7 m effective length, keeping the Poisson-simulated residual field in the central passage as low as 0.6 G.

BSY TOPOLOGIES

The first horizontal deflections of the splitting module are provided by Lambertson-type Septum Magnets. “Two-way” or “three-way” geometry LSMs can be adopted depending on the BSY topology.

Examples of possible BSY layouts are sketched in Fig. 2. Figure 2a) refers to the up to nine beamlines NGLS Spreader scheme. The scheme of Fig. 2b) combines “two-way” and “three-way” LSMs providing flexibility for a large variety of BSY layouts.

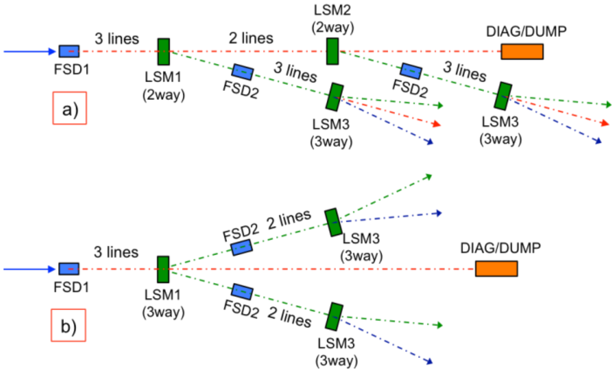

Figure 2: Examples of possible BSY layouts involving initial vertical splitting from Fast Switching Devices (FSD) and Two- and Three-way Lambertson Septum Magnets (LSM).

SC RF-DIPOLE CAVITY

The superconducting rf-dipole cavity shown in Fig. 3 is geometry favorable at low frequencies and has low surface fields and high shunt impedance. The rf properties of this preliminary design are presented in Table 1. The detailed optimization performed has shown that the cylindrical geometry with trapezoidal-shaped loading elements delivers improved rf properties [3]. The required transverse voltage V_T = 4 MV can be achieved by one cavity with peak surface electric field of 23 MV/m and peak surface magnetic field of 32 mT. The low peak surface fields can be easily achieved as demonstrated in Ref. [4]. The rf power requirements for the operating mode are below 5 W for both 2.0 K and 4.2 K, assuming a residual surface resistance R_{res} of 10 nΩ.

With adequately damped higher order modes (HOMs), the beam loading compensation is determined considering only for the fundamental mode. Hence the corresponding loaded quality factor (Q_L) is 5.5×10^6 at a beam offset of Δx = 5 mm where the transverse voltage variation is as low as $\delta V_T = 0.002\ V_T$. This requires additional rf power of 1.4 kW in beam loading compensation for the average beam current I_0 of 0.02 mA that varies linearly with beam current. The resultant loaded bandwidth is ~60 Hz.

Table 1: SC Rf-Dipole Cavity (at V_T = 4 MV)

Parameter	Value	Units
Frequency	325	MHz
Nearest HOM	508	MHz
Cavity length/diameter	696/340	mm
Beam aperture	40	mm
$[R/Q]_T$	2133	Ω
R_TR_S	1.95×10^5	Ω^2
E_P (Peak electric field)	23	MV/m
B_P (Peak magnetic field)	32	mT
Operating temperature	2.0/4.2	K
Surface resistance	10.9/58.7	nΩ
Q_0	$8.4/1.6\times10^9$	
P_{diss} RF power	0.9/4.8	W
Q_L	5.5×10^6	
Loaded bandwidth	59	Hz

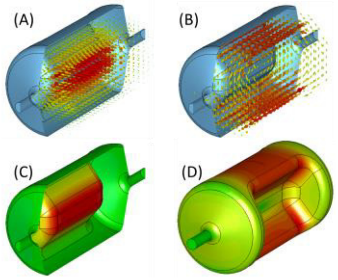

Figure 3: (A) Electric field, (B) magnetic field, (C) surface electric field, and (D) surface magnetic field of the rf-dipole cavity.

NC RF-DIPOLE CAVITY

The normal conducting rf-dipole cavity shown in Fig. 4 was designed by scaling and optimizing the 139 MHz design proposed for NGLS [5] with a beam aperture of 25 mm. The design and rf-parameters are listed in Table 2. The transverse shunt impedance is increased significantly with reduced the beam aperture that increases the transverse $[R/Q]_T$ in the normal conducting design. The peak surface electric field does not exceed the Kilpatrick criterion. The proposed design has a transverse shunt impedance of 86 MΩ that requires 6 rf cavities in achieving the required deflection. A single cavity is required to deliver a deflection of 0.67 MV operating at a power dissipation of 5.2 kW with cooling requirements as low as 4.4 W/cm^2 per cavity, for OFE–Cu with conductivity of $\sigma = 5.8\times10^7$ S/m and corresponding surface resistance of $R_s = 4.7$ mΩ.

Table 2: NC Rf-Dipole Cavity (at V_T = 4 MV)

Parameter	Value	Units
Frequency	325	MHz
Nearest HOM	518	MHz
Cavity length/height/width	370 / 261 / 150	mm
Beam aperture	25	mm
Bar length/height	305 / 15	mm
$[R/Q]_T$	8367	Ω
$R_T R_S$	4×10^5	Ω^2
E_P (Peak electric field)	28	MV/m
B_P (Peak magnetic field)	33	mT
Q_0	1.03×10^4	
No. of cavities	6	
P_{diss}/cav (V_T = 0.67 MV)	5.2	kW
Peak dP$_{diss}$ / dA per cavity	4.4	W/cm^2

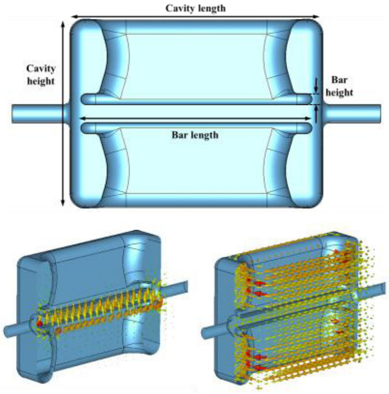

Figure 4: Schematic of normal rf-dipole cavity (top) with electric field (bottom left) and magnetic field (bottom right) profile.

NC 4-ROD CAVITY

The single cell 4-rod cavity design shown in Fig. 5 is adapted from the 499 MHz normal conducting 4-rod rf separator cavity that is currently in operation in CEBAF at Jefferson Lab [6]. The net transverse voltage requirement of 4.0 MV can be possibly achieved by 4 cavities, with a power dissipation of 6.5 kW per cavity. However the resulting design has a high peak surface magnetic field (B_P) due to high surface magnetic field at the rod ends, and requires a higher cooling requirement of 36 W/cm^2 per cavity that can be achieved with similar parallel cooling mechanism as used in the 499 MHz rf separator cavities.

Table 3: NC 4-Rod Cavity (at V_T = 4 MV)

Parameter	Value	Units
Frequency	325	MHz
LOM / Nearest HOM	226 / 349	MHz
Cavity length/diameter	450 / 444	mm
Beam aperture	25	mm
Rod length/diameter	208 / 31	mm
$[R/Q]_T$	1.9×10^4	Ω
$R_T R_S$	7.2×10^5	Ω^2
E_P (Peak electric field)	29	MV/m
B_P (Peak magnetic field)	63	mT
Q_0	8.0×10^3	
No. of cavities	4	
P_{diss}/cav (V_T = 1.0 MV)	6.5	kW
Peak dP$_{diss}$ / dA per cavity	36	W/cm^2

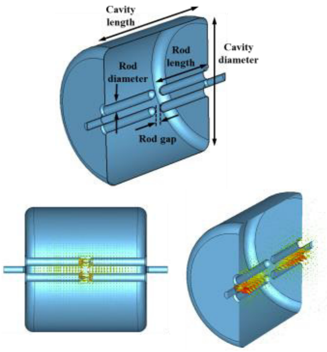

Figure 5: Schematic of normal conducting 4-rod cavity (top) with electric field (bottom left) and magnetic field (bottom right) profile.

CONCLUSION

A compact RF beam spreader concept and preliminary design options of three possible deflecting cavities for the LCLS-II are presented in alternative to the kicker-based scheme presently under consideration.

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