Title

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COMPACT SPREADER SCHEMES

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This paper describes beam distribution schemes adopting a novel implementation based on low amplitude vertical deflections combined with horizontal ones generated by Lambertson-type septum magnets. This scheme offers substantial compactness in the longitudinal layouts of the beam lines and increased flexibility for beam delivery of multiple beam lines on a shot-to-shot basis. Fast kickers (FK) or transverse electric field RF Deflectors (RFD) provide the low amplitude deflections. Initially proposed at the Stanford Linear Accelerator Center (SLAC) as tools for beam diagnostics and more recently adopted for multiline beam pattern schemes, RFDs offer repetition capabilities and a likely better amplitude reproducibility when compared to FKs, which, in turn, offer more modest financial involvements both in construction and operation. Both solutions represent an ideal approach for the design of compact beam distribution systems resulting in space and cost savings while preserving flexibility and beam quality.

INTRODUCTION

Modern Linac-based Free Electron Laser (FEL) systems are often equipped with multiple beam lines which require a beam switchyard (BSY) to distribute electron bunches from the Linac to individual FELs. The BSY design is challenging, as it requires not only to preserve beam quality and provide flexible bunch repetition rate, but also to meet the physical constraint of the facility site. In this paper we present designs of compact Beam Switchyard (BSY) systems. Fast Switching Devices (FSD) like Fast Kickers (FK) or RF Deflectors (RFD) initiate a low-amplitude vertical splitting. Septum magnets installed downstream as the vertical separation between the trajectories matches the magnet apertures provide the first horizontal deflections. The resulting schemes represent an ideal solution for the design of compact beam distribution systems resulting in space and cost savings while preserving flexibility and beam quality in a variety of Beam Switch Yard topologies.

Transverse deflecting RF structures, originally proposed at SLAC [1] and at the Thomas Jefferson National Accelerator Facility (TJNAF) [2] as tools for beam separation, space phase 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 [5,6]. The adoption of transverse RF deflectors allows distributing electron bunches with on-demand repetition rates in each line, well above the few hundred kHz limit likely represented by fast kickers. In addition, the steady state nature of the CW transverse fields provides higher deflection stability and shot-to-shot reproducibility as compared to those achievable with fast kickers where the deflecting pulses are created at every bunch passage. Beam distribution schemes adopting cascading RF deflectors have been discussed in [7] and complement this paper.

Conversely, the technology associated with stripline- and ferrite-based Fast Kickers is well developed and their use represents a more attractive solution from the financial investment point of view.

Issues related to Machine Protection also play an important role in the choice between the two options.

THE INITIAL SPLITTING MODULE

Stability and reproducibility criteria require the deflections from the fast switching devices to be of the order of 1-mrad or less. A BSY layout based on reduced amplitude initial horizontal deflections would involve very long beam lines to provide clearance to the downstream deflecting and focusing elements.

Schemes involving an initial splitting in the vertical direction further combined with horizontal deflections provided by properly designed Lambertson-type septum magnets (LSM) located at a short distance downstream offer instead options for substantial reductions in the longitudinal extent of the beam lines. The LSM thin septum accepts a contained vertical separation between the trajectories allowing the magnet to be installed at a relatively short distance from the fast switching devices, resulting in a more compact longitudinal footprint of the BSY layout.

In the basic splitting module scheme shown in Figures 1 and 2 an initial section produces three vertical trajectories selectively deflected by the LSMs. Two-way and three-way Lambertson magnet options can be adopted depending on the chosen BSY topology.

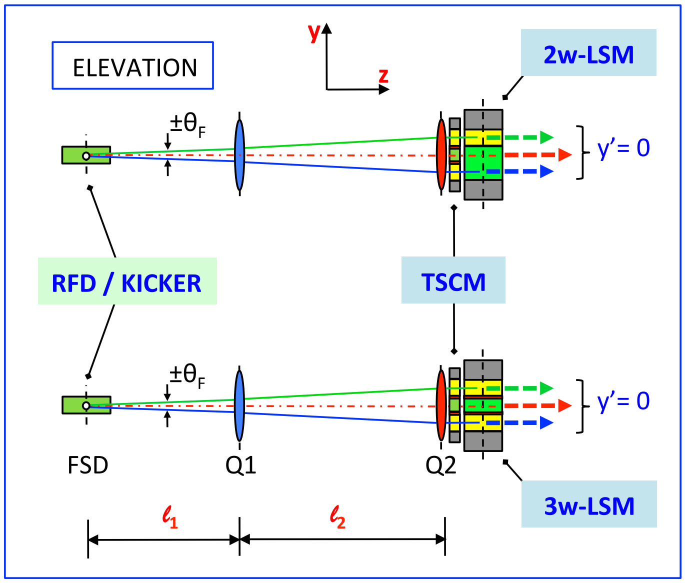

Fig. 1: Elevation of the basic module of the initial vertical splitting scheme. A Fast Switching Device (FSD) vertically splits an incoming bunch train into three trajectories with a small amplitude angle $\pm\theta_F$. The initial slopes, enhanced by the vertically defocusing quadrupole Q1, are compensated at the entrance of the LSM downstream.

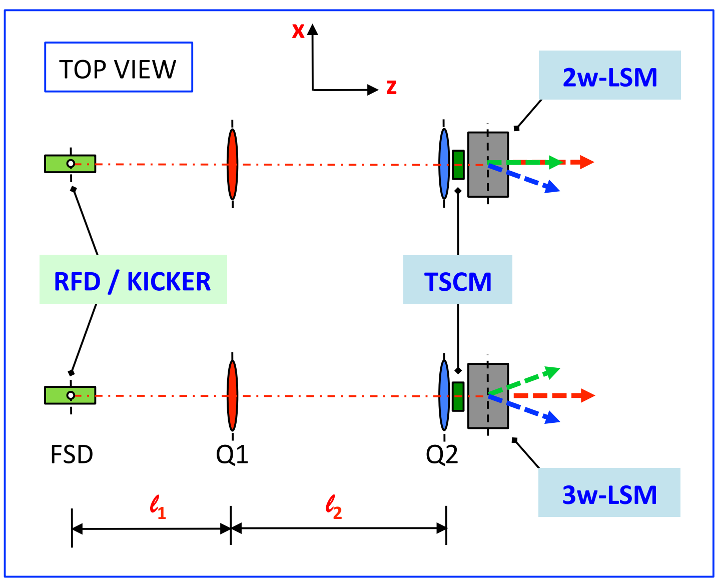

Fig. 2: Top view of the basic module of the initial vertical splitting scheme showing the role of two- or a three-way LSM installed at a relatively short distance from the FSD.

Vertical splitting

A Fast Switching Device, either a bipolar kicker or an RFD, vertically splits an incoming bunch train into three trajectories, two deflected and one straight. The small amplitude deflections are enhanced by the vertically

defocusing quadrupole Q_1 while the Q_2 location defines the trajectories separation Δy. A Twin Septum Corrector Magnet (TSCM) or Q_2 compensate[*] the slopes $\Delta y'$ at the LSM entrance.
The scheme consists of a telescopic arrangement of elements governed by the vertical transfer matrix from the FSD to the LSM with the constraints:

$$R^y_{12} = \Delta y / \theta_F \; , R^y_{22} = 0. \tag{1}$$

Solving (1) with the compact arrangement condition

$$l_1 + l_2 = \min \tag{2}$$

gives, in thin lens approximation:

$$l_{1,2} \equiv l = -f_1 + \sqrt{f_1(f_1 + R^y_{12})} \quad , \quad f_2 = l\left(\frac{2f_1 + l}{f_1 + l}\right) \tag{3}$$

where f_1 and f_2 are the Q_1 and Q_2 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. The quoted focal lengths are consistent with a 0.6-T B_{TIP} value at 4-GeV beam energy for 0.15-m long standard quadrupoles with 20-mm and 60-mm respective bore diameters offering comfortable apertures for the local trajectory separation.

Horizontal Deflection: Dedicated Magnets

LSM magnets provide the first horizontal deflections. A typical two-way LSM is shown in Figure 3 in upright configuration. In this design, originally conceived for the three-way RFD deflecting scheme of the Next Generation Light Source (NGLS) project at the Lawrence Berkeley National Lab, the zero-field passage has a relatively large internal diameter to accommodate two un-deflected trajectories while the other one is right deflected to create the first branch of the spreader. A 2-mm thin septum separates the deflecting gap from the field-free region.

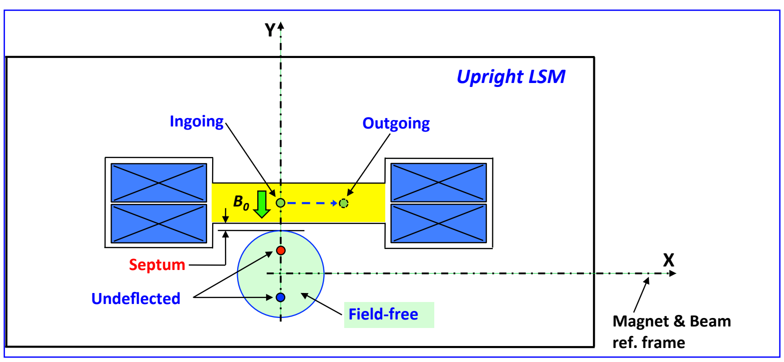

Fig. 3: Cross section of a two-way upright LSM magnet. The top trajectory (green) is deflected to the right while the two others travel un-deflected in the field-free channel.

A Poisson's simulation for the LSM of Figure 3 anticipates (Figure 4) a residual field in the field-free region with components

$$B^{res}_x = 0.74\,G \, , B^{res}_y = 2.4\,G. \tag{4}$$

The 0.33-T design figure of the main deflecting field and the <2.5-G residual B-field in the field-free region provide 25-mrad and about 20-μrad deflections respectively for a 4-GeV beam. A parameter list for the two-way LSM is given in Table 1.

[*] Arguments supporting slope compensations are developed in a subsection below.

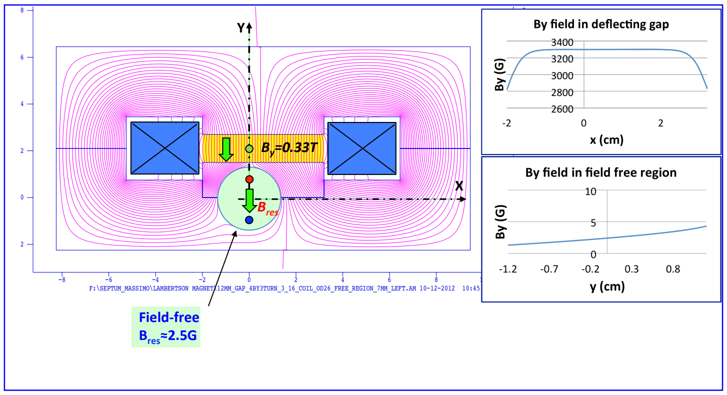

Fig. 4: Poisson simulation of the field strengths for the magnetic circuit of Figure 3. A 2-mm thin septum contains the residual B-field down to 0.8×10^{-3} the main one.

Table 1: Parameter list for a two-way LSM.

Two-way Lambertson Parameters		
Magnet type	Window frame	
Deflection	mrad	25.0
Energy	GeV	4.0
Incoming beam sep.	mm	±15.0
Field strength	Tm	0.330
Eff. Length	m	1.0
Septum	mm	2.0
Defl. Gap height	mm	12.0
Main B-field	T	0.33
Residual B-fileld	G	~3
Coils		2 x 10 turns
Magnet Current	A	158.0
Magnet Power	kW	1.27

In compact beam distribution schemes it is sometimes useful to concentrate two horizontal opposite deflections in a single LSM still leaving the option for an un-deflected trajectory. A design of a three-way LSM, with a central zero-field region separating two deflecting gaps, is shown in Figure 5. The cylindrical vacuum pipe is installed in a rectangular cross section passage for easier yoke construction.

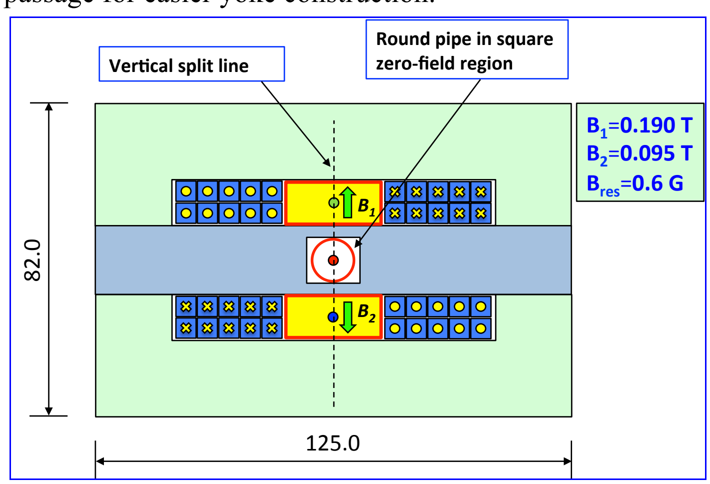

Fig. 5: Cross section of a three-way "asymmetric" LSM. The magnet can provide opposite deflection differing by up a factor of two while keeping the residual field below 0.6-G. Dimensions are in mm.

In a basic scheme the same amplitude opposite B-fields fully compensate the residual field in the central passage. A more flexible solution is proposed with the present “asymmetric deflection” design where different amplitude deflections are available. The 0.7-m long magnet provides up to 5- and 10-mrad opposite deflections to a 4-GeV beam. The Poisson-simulated magnet properties (Figure 6) anticipate a ~0.6-G residual field in the central passage and a 0.7×10^{-3} radial non-homogeneity of the main deflecting fields. Table 2 gives a parameter list for the three-way LSM sketched in Figure 5.

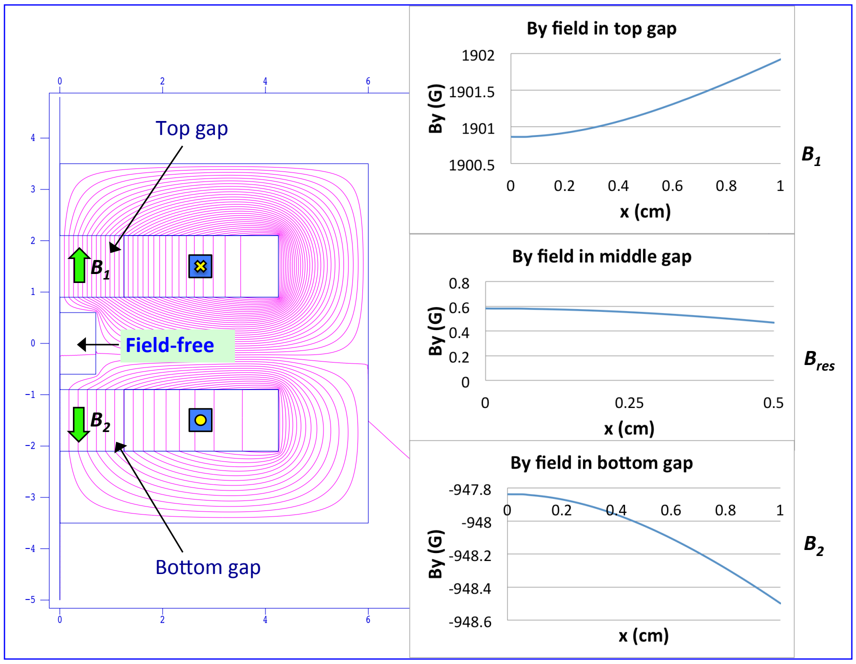

Fig. 6: Poisson simulation for the three-way LSM cut at the vertical symmetry plane. The B-field distributions in the two deflecting gaps are plotted together with the associated residual field in the zero-field channel.

Table 2: Parameter list for a three-way LSM.

Three-way Lambertson Parameters		
Magnet type	Twin window frame	
Deflection	mrad	10.0 / 5.0
Energy	GeV	4.0
Incoming beam sep.	mm	±15.0
Field strength	Tm	0.133 / 0.067
Eff. Length	m	0.70
Septum	mm	3.0
Defl. Gap height	mm	12.0
Main B-field	T	0.19 / 0.095
Residual B-fileld	G	~0.6
Coils		2 x 10 turns
Current	A	184.0 / 92.0
Power	kW	0.595 / 0.149

The Twin Septum Magnet (TSM) shown in Figure 7 is a simplified version of the three-way LSM that can be used to provide simultaneous opposite deflections to two incoming trajectories. The two deflecting gaps are separated by a thicker septum than in the LSM and provide opposite sign B-fields. A Poisson simulated TSM performance suggests an 8-mm septum thickness in the 2x0.19-T equal B-fields configuration, and 6-mm in the non-equal deflection case of Figure 5, to contain the field in the septum around 1.3-T. With the shown geometry the incoming beam separation is in the range of 18- to 20-mm. A parameter list for the TSM is given in Table 3.

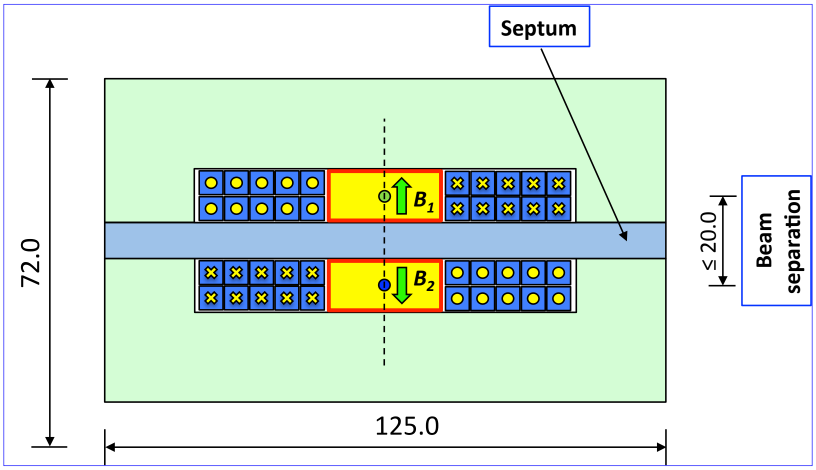

Fig. 7: Cross section of a Twin Septum Magnet (TSM) providing equal amplitude opposite deflection. Optional non-equal deflections are possible requiring smaller septum thickness. Dimensions in mm.

Table 3: Parameter list for a two-way TSM.

TSM Parameters		
Magnet type	Twin window frame	
Deflection	mrad	±10.0
Energy	GeV	4.0
Incoming beam sep.	mm	±10.0
Field strength	Tm	0.133
Eff. Length	m	0.70
Septum	mm	8.0
Defl. Gap height	mm	12.0
Main B-field	T	0.19
Coils		2 x 10 turns
Current	A	184.0
Power	kW	1.2

A Poisson simulation for the TSM anticipates a B-field constant across the gaps width with coefficients

$$G_y = 1.1 \cdot 10^{-2}\ G/mm\,,\ \ S_y = 1.0 \cdot 10^{-2}\ G/mm^2. \tag{5}$$

SLOPE COMPENSATION

In a vertical initial splitting scheme it is essential to foresee early compensation of the vertical slopes of the trajectories deflected by the FSDs to avoid the development of large offsets along the beam path and the use of wide aperture correctors downstream. Slope compensations can be achieved in different ways.

Rolled LSMs

An LSM rotated around the beam direction (Figure 8) introduces a vertical steering via the horizontal component of the main B-field.
The amount of rotation depends on the required steering amplitude and is usually in the range of a few degrees. The roll direction defines the sign of the compensation steering. From the cyclotron equation

$$p \equiv \beta E/c = eB\rho \tag{6}$$

the development of the trajectory deflections along the integrated field strengths at a given beam energy E reads, in practical units (relativistic case, β=1):

$$\theta_{x,y}(s) = \frac{c\int B_{y,x}\,ds}{\beta E/e} \cong 0.3\,L_m \frac{B_{y,x}}{E} \quad \text{[GeV, T, m]} \tag{7}$$

where $\theta_{x,y}$ are the LSM deflections associated to the $B_{y,x}$ components of the main field assumed constant along the magnet effective length L_m. The roll angle α is then

$$\alpha = \tan^{-1}\left(\frac{B_x}{B_y}\right) = \tan^{-1}\left(\frac{\theta_y}{\theta_x}\right) \ . \tag{8}$$

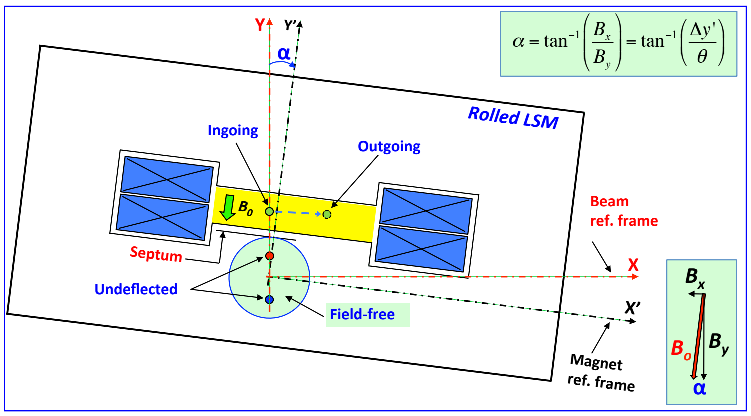

Fig. 8: Vertical steering from a rotated LSM.

To provide the same deflection as an upright LSM, the rolled LSM must have the same vertical B-field component and its excitation is retuned according to

$$B_0^{roll} = \frac{B_0^{upr}}{\cos\alpha} \ . \tag{9}$$

Septum Corrector Magnets

Septum-type Corrector Magnets (SCM) can be used to selectively compensate the slopes of trajectories spatially very close to each other, when their separation prevents the use of standard, single beam correctors. In this case the steering direction lies in the same plane of the incoming trajectories so the septum thickness and the beams separation are set by the size of the coil conductor, differently from the LSM case. The following examples deal with trajectory separation and steering direction in the vertical plane.
The septum corrector sketched in Figure 9 vertically steers the incoming line-2 parallel to the un-deflected line-1. The 5-mm septum thickness imposes a ~16 mm separation between the incoming trajectories.

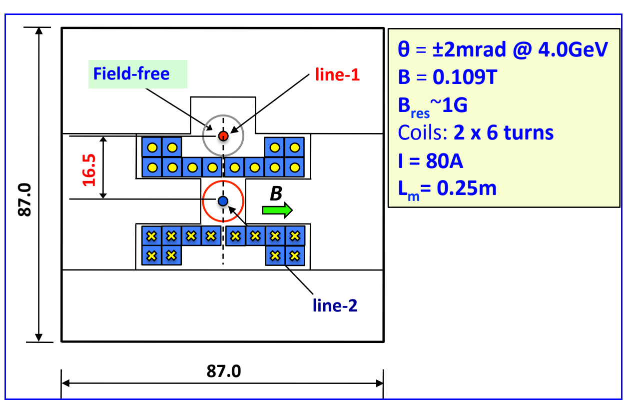

Fig. 9: Cross section of a compact SCM corrector for the vertical steering of line 2. Dimensions are in mm.

The Poisson simulation of Figure 10 anticipates a ~1-G residual field in the central region and a 0.1-T main B-field in the deflecting gaps with a 6-polar coefficient

$$S_y \cong 2.8\,G/mm^2\,. \tag{5'}$$

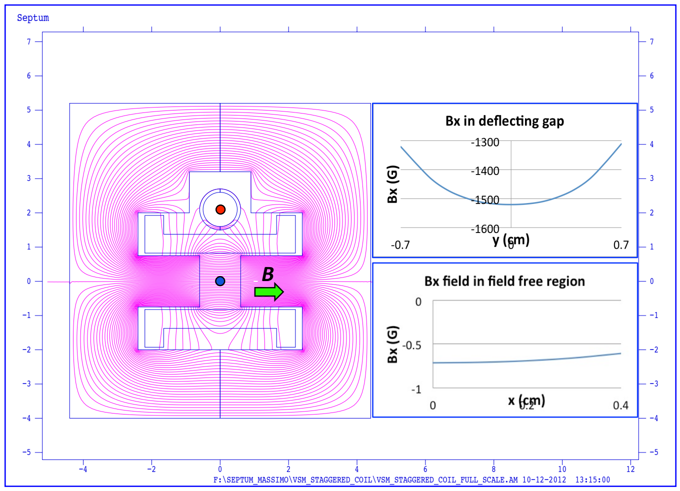

Fig. 10: Poisson simulation for the SCM vertical corrector. Shown is one quarter of the symmetric structure.

A twin septum corrector (TSCM) can be used to compensate the vertical slopes of the two trajectories at the exit of the vertically focusing Q_2 in the scheme of Figure 1, if the latter is part of a FODO system. A sketch of a TSCM magnet in "divergent" configuration is shown in Figure 11. Opposite sign B-fields provide independent converging or diverging vertical deflections to line-1 and line-3 and fully compensate the residual field in the central gap.

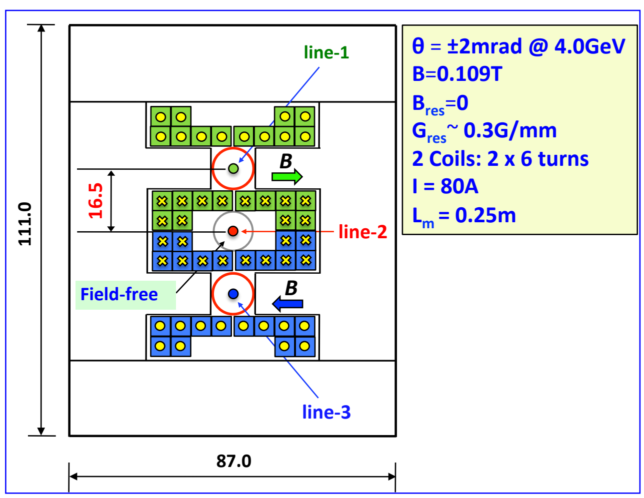

Fig. 11: Cross section of a compact TSCM corrector. Opposite sign B-fields provide converging or diverging vertical deflections and compensate the residual field in the central gap. Dimensions are in mm.

The Poisson simulation in Figure 12 anticipates the behavior of the main and residual horizontal B-fields characterized by the coefficients

$$\begin{aligned} &G_y^{main} = 213.2\,G/mm\,,\ \ S_y^{main} = -6.1\,G/mm^2 \\ &G_y^{res} = 0.28\,G/mm\,. \end{aligned} \tag{5''}$$

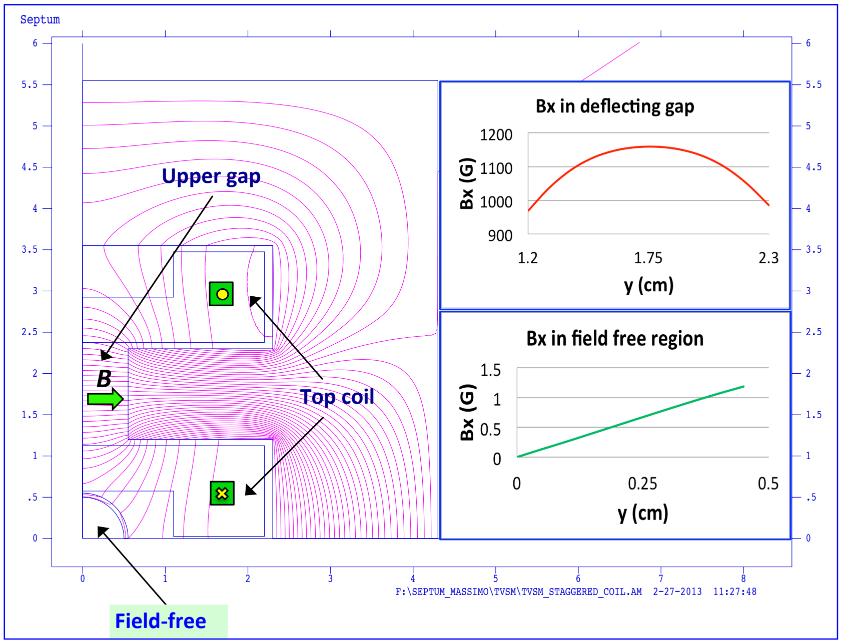

Fig. 12: Poisson simulation for one quarter of the symmetric structure of the TSCM corrector.

BSY TOPOLOGIES

Several BSY topologies can be realized combining the initial vertical splitting from Fast Deflecting Switches with dedicated deflecting elements like the "two- or "three-way" LSMs and the TSM. Examples of possible BSY layouts are sketched in Figure 13. Figure 13a) shows a possible evolution of the original right-side oriented scheme of the NGLS Spreader involving two and three-way LSMs. In Figure 13b) "three-way" LSMs and TSMs combine into a layout symmetric to the central line.

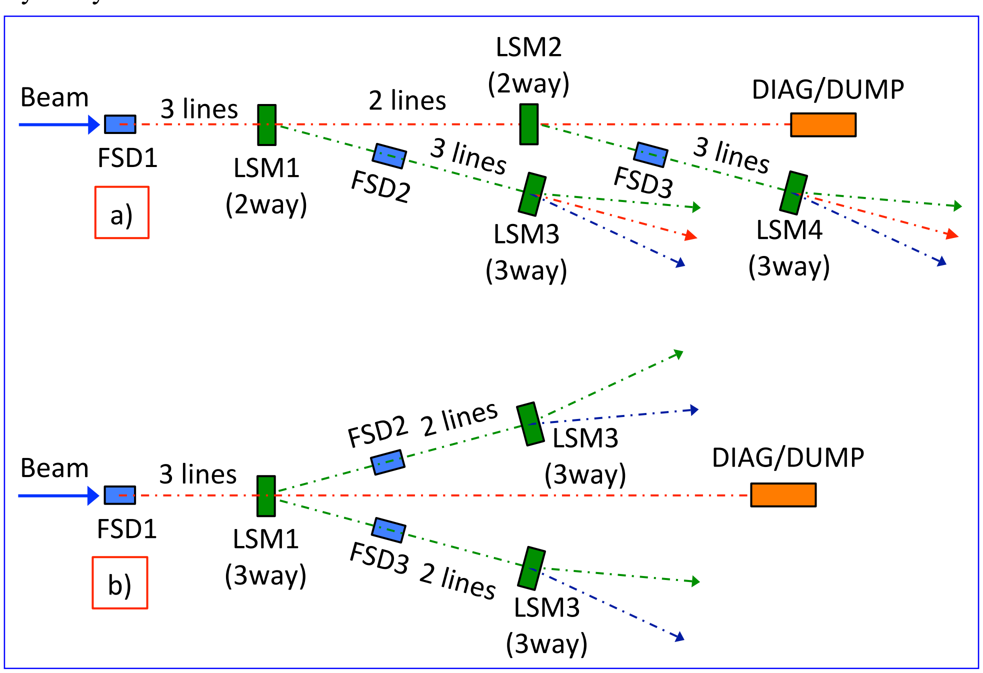

Fig. 13: Examples of BSY layouts involving initial vertical splitting from Fast Switching Devices (FSD) followed by horizontal deflections from combinations of Two- and Three-way Lambertson Septum Magnets (LSM).

SUMMARY

Compact beam spreader schemes combining vertical, small amplitude initial deflections from fast kickers or RF deflectors with horizontally bending Lambertson-type septum magnets offer several advantages in the design of compact beam distribution systems requiring flexibility and beam quality. The intrinsic nature of the CW RFD option is expected to offer higher deflection stability and reproducibility as compared to those from fast kicker technology and does not suffer from limitations in bunch repetition rates. Fast kicker solutions offer a much lower financial investment, both in construction and operation, when dealing with repetition rates in a few hundred kHz range. In both cases BSY layouts adopting vertical initial splitting schemes can feed multiple beam lines in very compact beam distribution schemes.

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