1. Evaluation of fringe field effect of the Booster bump magnets to the extracted beam trajectory in a scheme with increased distance between bump magnets.
2. Lattice functions perturbation at extraction in a scheme with pulsed bump-septum magnets.

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1 Introductions

It was recently found that linear optics of the Booster is significantly perturbed by the edge focusing of the injection and extraction orbit bumps. The maximum horizontal β_x is increased with respect to linear optics by 36% from 33.7 m to 46.0 m and dispersion by 94% from 3.2 m to 6.2 m; in the vertical plane, the maximum β_y is increased by 25% from 20.5m to 25.6 m. The edge focusing strength of a bending magnet is a function of bending angle θ and magnet length L:

$$K = -\frac{\theta^2}{L}. \tag{1}$$

Both sector and rectangular bending magnets produce focusing effect in only one plane, and sign of focusing does not depend on the sign of magnetic field. For the Booster doglegs, L is small (0.247 m) and θ is large (60 mrad). There are two doglegs (at Long03 and Long13 straight sections), each with 4 bending magnets.

The focusing effects are additive, giving rise to a significant amount of extra focusing ($0.115\ m^{-1}$, close to one main magnet which has $1/f = 0.157\ m^{-1}$) and leading to a big perturbation to the linear lattice.

The most effective way to mitigate edge focusing effect is based on the distance increasing between magnets, that permits to reduce bending angle. This allows to decrease horizontal β_x by 29% and dispersion by 74% in the Booster if space between magnets in both Long03 and Long13 straight sections is increased by 0.56 m. If this is done in the Long03 straight section only it reduces horizontal β by 15% (to 40.5 m) and dispersion by 46% (to 4.65 m). The last scheme will be realized during the summer shutdown as a short-term solution to mitigate the problem.

As a long term solution the new design of injection and extraction was proposed with increased distance between magnets in the injection bump and with extraction bump used only at the accelerator top energy with extraction septum located behind the envelope of the beam at injection. The lattice function perturbations are reasonably small in this case. Unfortunately this solution requires sufficient amount of design and construction work and is pretty expensive.

Maximum value of $\beta_{x,y}$ and dispersion at injection for different solutions of injection and extraction in the Booster are presented in Table 1. The fringe field effect of the Booster bump magnets to the extracted beam trajectory in a scheme with increased distance between bump magnets and lattice function perturbation at extraction in a scheme with pulsed bump-septum magnets are evaluated in this note.

2 Fringe field effect of the Booster bump magnets to the extracted beam trajectory

The proposed layout and strength of the new extraction system are presented in Fig. 1 and Table 2. An extracted beam passes pretty close to the dogleg magnets gap in a strong fringe fields (Fig. 2) that may effect extracted beam trajectory displacement, and possibly may require realignment of sufficient part of extracted beam line.

The circulating and extracted beam trajectories, β functions, dispersion and beam half-size at extraction in the Booster Long-02 and Long-03 straight sections for the new scheme are shown at Figs. 3 and 4. Vertical phase space and beam population at the center of the first vertical magnet of extracted beam line are

	$\Delta\beta_x$	$\Delta\beta_y$	ΔD	$\Delta\nu_x$	$\Delta\nu_y$
	%	%	%		
without injection and extraction bumps	100	100	100	0.000	0.000
with existing injection and extraction bumps	136	125	195	0.069	0.011
without extraction bump at Long13	118	124	144	0.032	0.027
distance between magnets increased by 0.56 m at Long03 and Long13	107	124	120	0.012	0.015
3-magnet extraction bumps with distance between magn. increased by 0.56 m at Long03 and Long13	104	126	114	0.006	0.032
distance between magnets increased by 0.56 m at Long03	121	124	148	0.037	0.013
3-magnet extraction bumps with distance between magnets increased by 0.56 m at Long03	118	125	143	0.034	0.019
new injection and extraction schemes	104	117	111	0.003	0.024

Table 1: Maximum of β_x, β_y, dispersion and betatron tune deviation at injection for different solutions of injection and extraction schemes in the Booster. Betatron tune without injection and extraction bumps is $\nu_x = 6.70$, $\nu_y = 6.80$.

shown in Figures 5 and 7 for calculated fringe field (Fig. 6) at the extracted beam trajectory in the dogleg magnets number 3 and 4. As shown in Figs. 8 a compensation of this effect can be obtained by displacement of magnet number 3 down and magnet number 4 up by (155.73mm-124.44mm)/2=15.6 mm from the designed position (see Fig. 2). Fringe field gradient is calculated from Fig. 6, and is equal to $G = -3.862\ T/m$ in the magnet number 3, $G = +2.219\ T/m$ in the magnet number 4, and $G = \mp 3.329\ T/m$ in the magnet number 3 and 4 with magnets displacement for field effect compensation.

The sextupole component of magnetic field in the Booster bump magnets is pretty big. But as the sextupole components are approximately equivalent in these magnets, and sign of current is different, this displacement will compensate (in first approximation) sextupole component effect of these magnets to the circulating beam stability.

Table 2: Strength of extraction magnets.

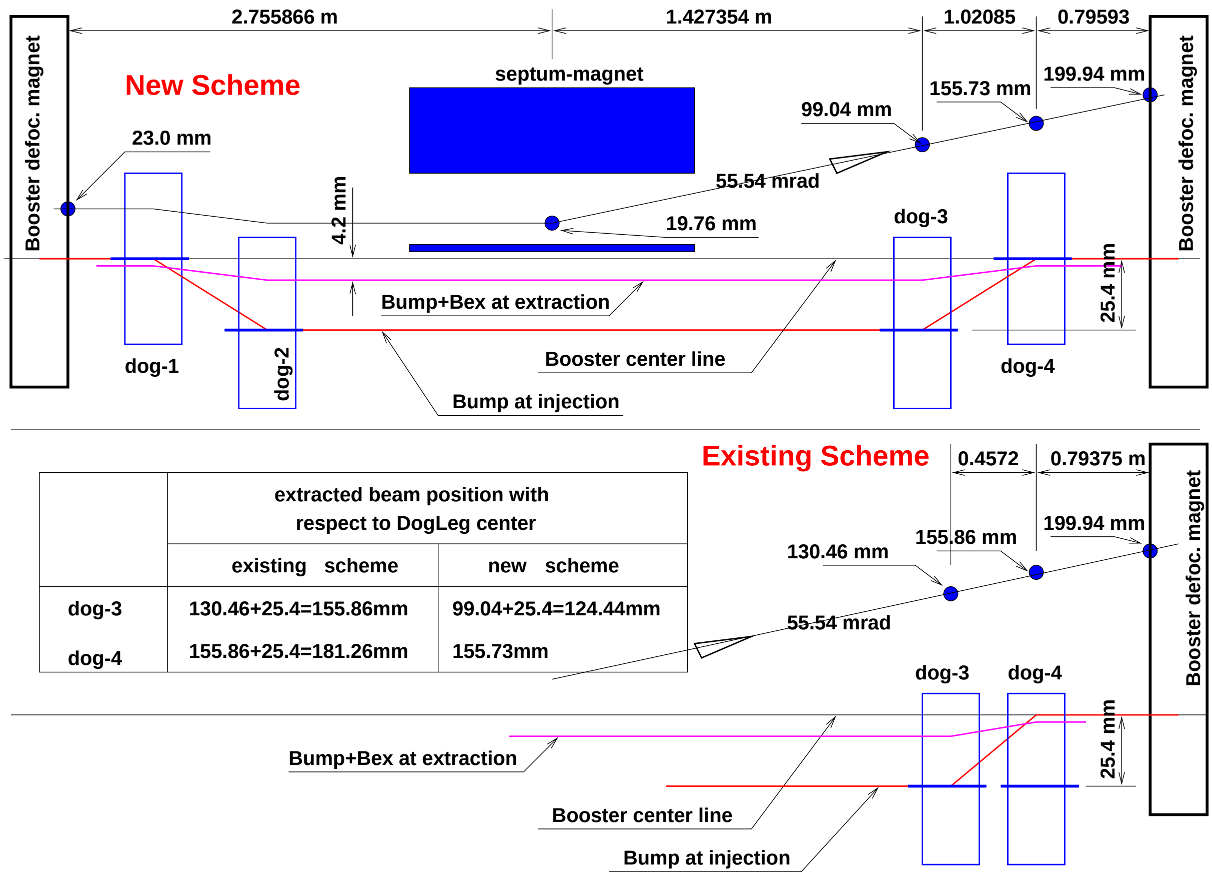
element	location	length	Magnetic field	bending angle
		m	kG	mrad
MKS02-1,2,3,4	Long-02	1.08	0.08388	1.222, (4 magnets)
IBEX02	Long-02	0.265	0.0903	0.0807
DOG03-1,2,3,4	Long-03	0.24722	3.018	2.5164, (1 magnet)
SEPTUM03	Long-03	1.524	10.85752	55.807

3 Evaluation of lattice functions perturbation at extraction in a scheme with pulsed bump-septum magnets

Table 3: Booster lattice functions at the center of Long03 with new extraction bump with increased distance between magnets, and with pulsed septum-bump magnets. The edge focusing strength of one bump magnet for different schemes is shown in the bottom of this table.

	increased distance between magnets	pulsed bump-septum magnets
β_x, m	6.162	6.070
α_x	0.074	0.073
β_y, m	20.002	20.003
α_y	0.021	0.021
dispersion D, m	1.847	1.870
dispersion D’	0.000	-0.001
K=θ^2/L at injection	0.000500	-
K=θ^2/L at extraction	0.000006	0.001500
K=θ^2/L at injection for existing scheme	0.009000	
K=θ^2/L at extraction for existing scheme	0.000100	

The new proposed extraction bump at Long-03 straight section with pulsed bump-septum magnets used only at the top energy and septa located outside of the main magnet aperture is shown in Fig. 9.



	extracted beam position with respect to DogLeg center	
	existing scheme	new scheme
dog-3	130.46+25.4=155.86mm	99.04+25.4=124.44mm
dog-4	155.86+25.4=181.26mm	155.73mm

Figure 1: Extracted beam trajectories in the Booster Long-03 straight section for the new (top) and existing (bottom) schemes.

The horizontal and vertical β functions and horizontal dispersion at the accelerator top energy in the extraction region (Long03) are shown in Fig. 10 for the new extraction bump with increased distance between bump-magnets and for the scheme with pulsed bump-septum magnets used only at the top energy. A comparison of the Booster lattice functions for these two cases at the center of Long03 is presented in Table 3. The edge focusing strength of one bump magnet shown in this table is a factor of 6 less at the top energy for the scheme with pulsed magnets compared to this strength at injection in the existing Booster. Along with a factor of 3 less circulating beam size at the top energy this should not effect a problem at extraction.

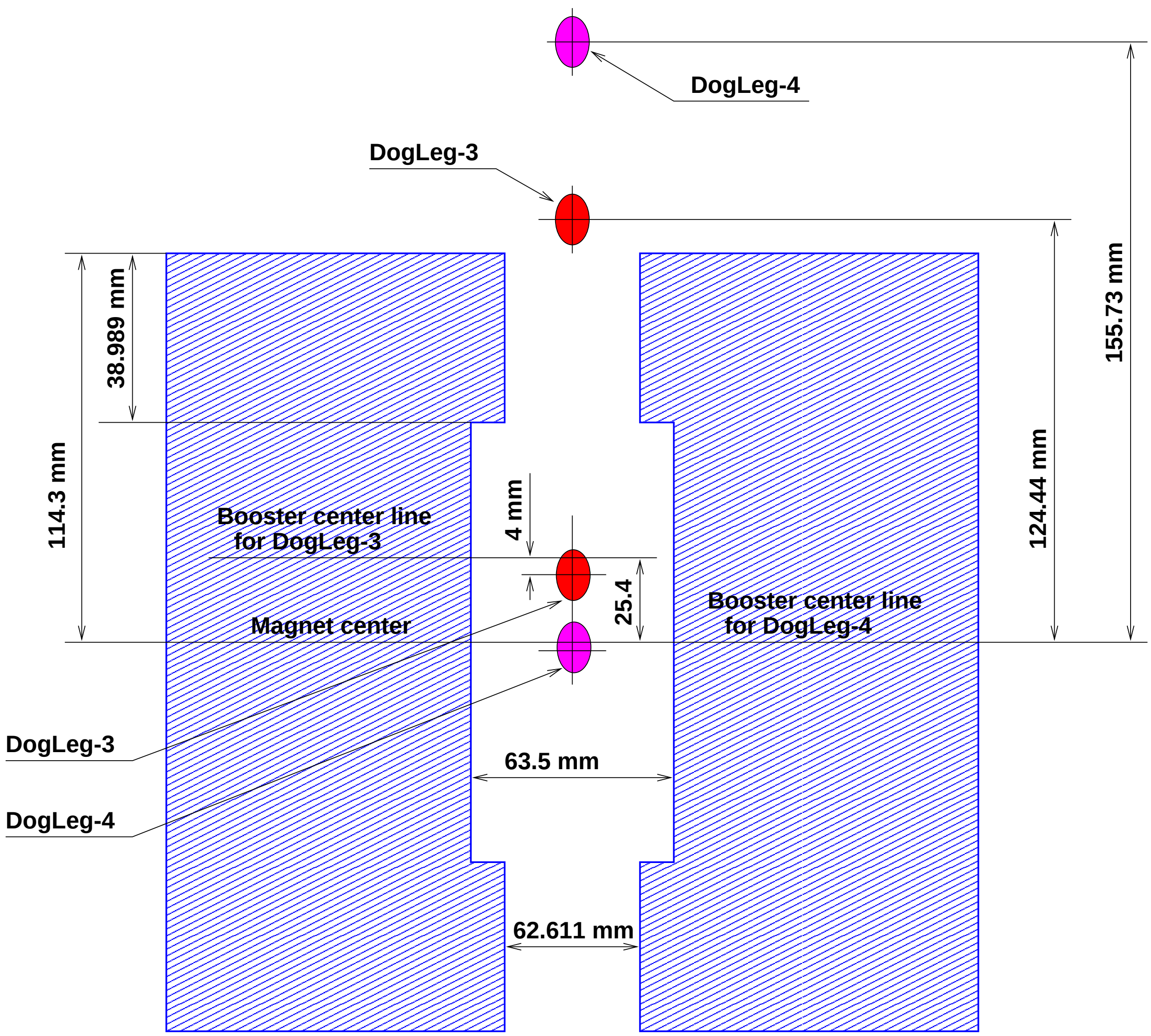


Figure 2: Extracted and circulating beam positions in the Booster DoLeg-3 and DoLeg-4 for new scheme.

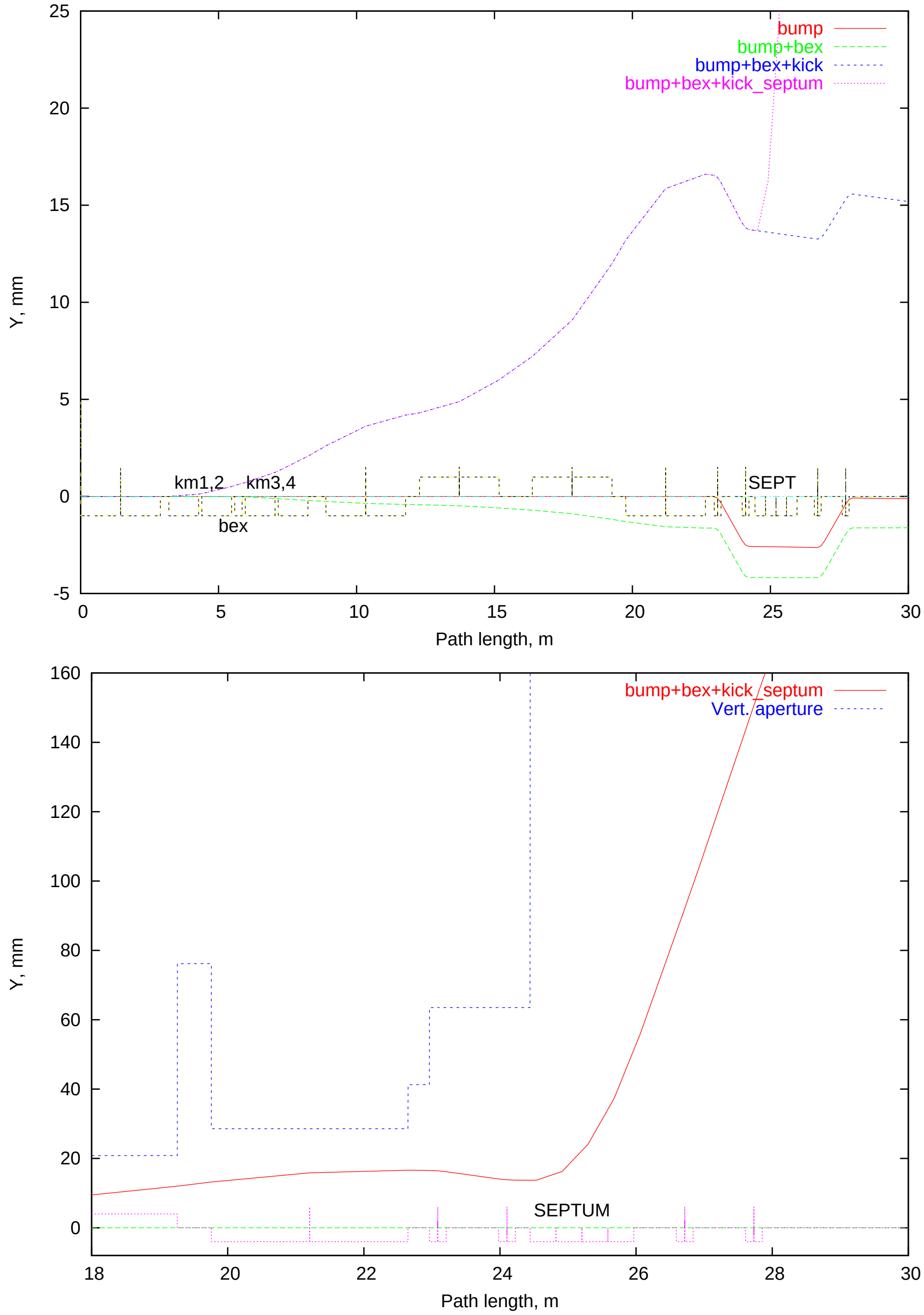


Figure 3: Circulating (top) and extracted (bottom) beam trajectories in the Booster Long-02 and Long-03 straight sections for the new scheme.

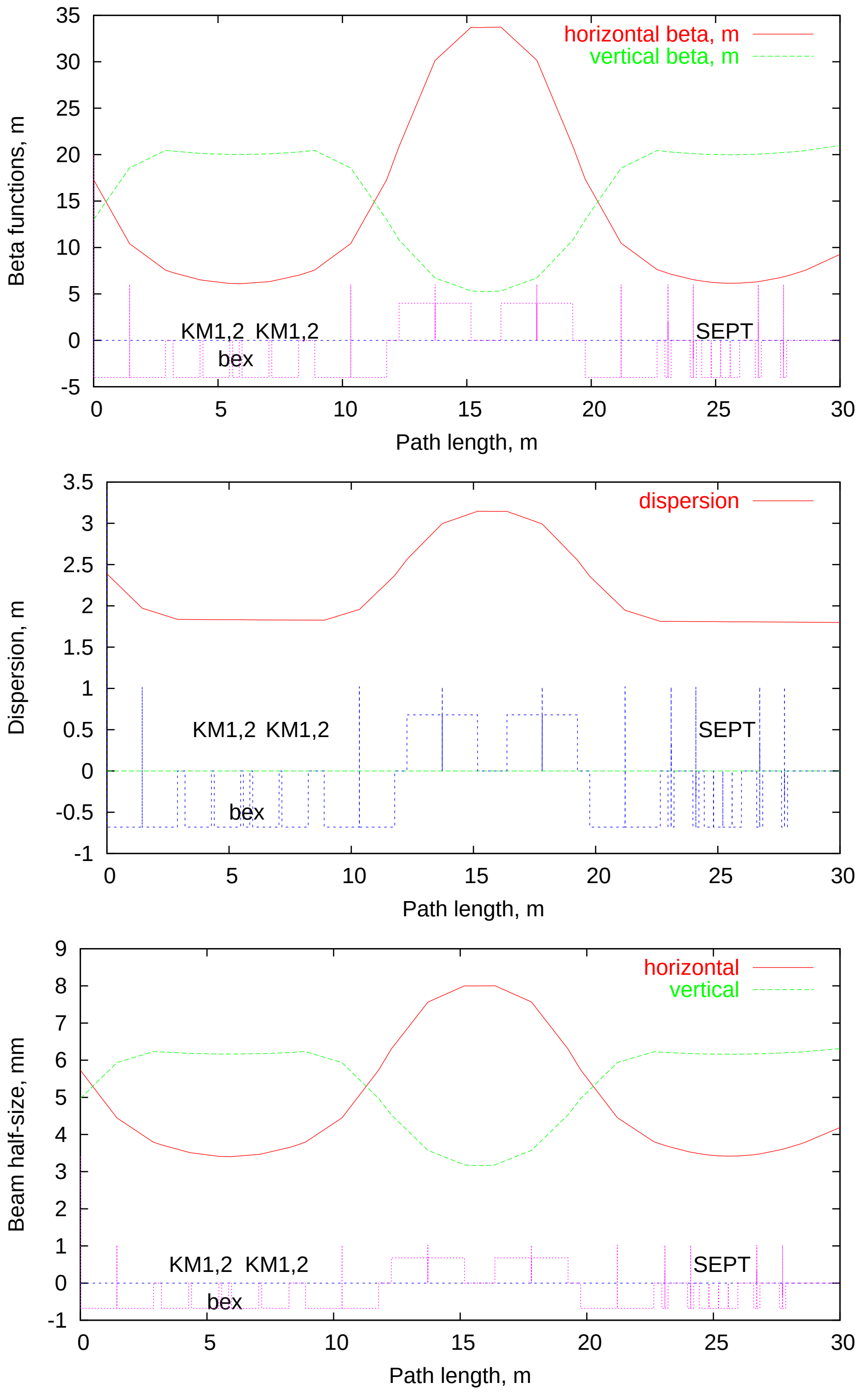


Figure 4: β functions (top), dispersion (middle) and beam half-size at extraction in the Booster Long-02 and Long-03 straight sections. Normalized emittance at 95% is 12 mm.mrad.

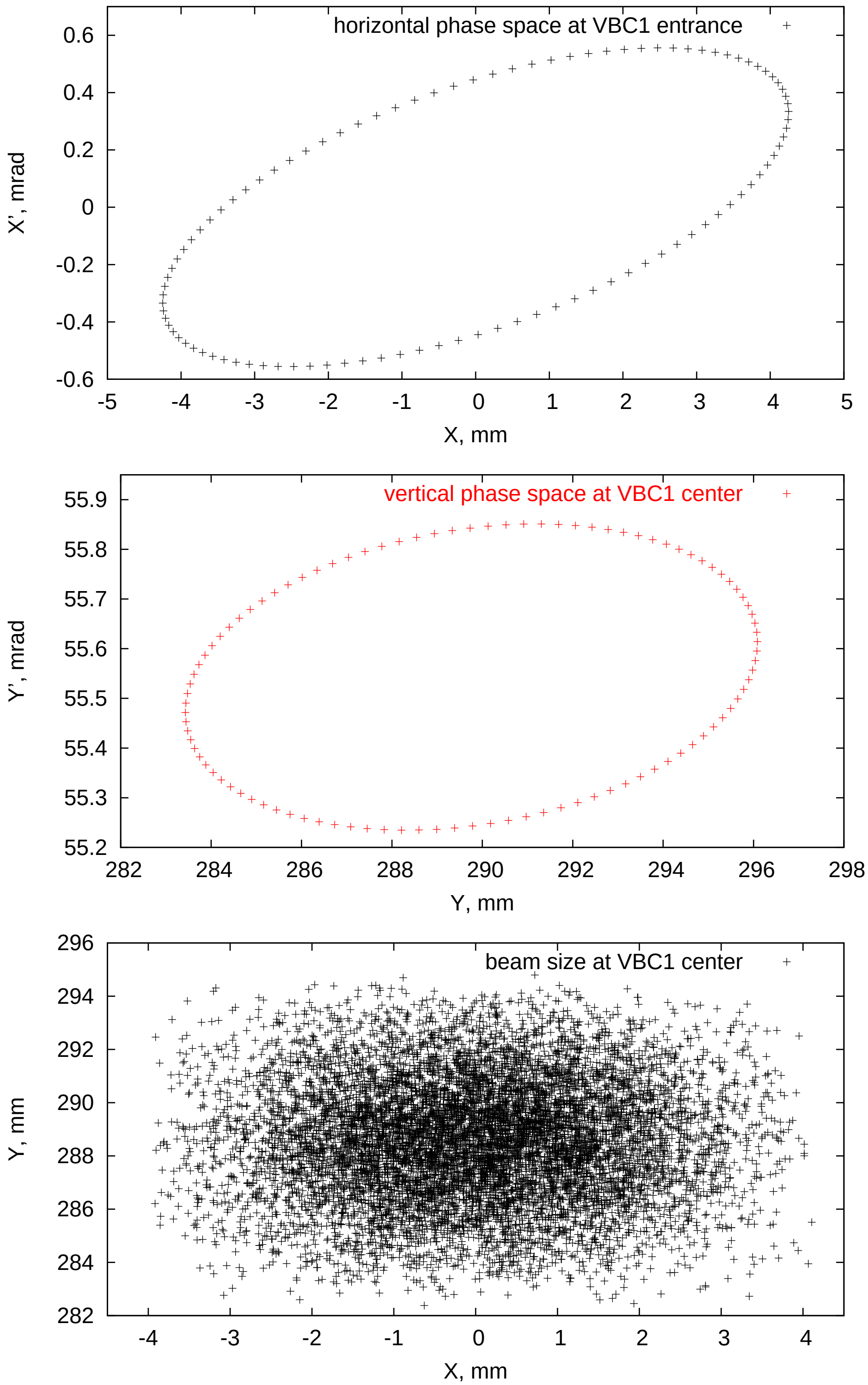


Figure 5: Horizontal (top), vertical (middle) phase space and beam population (bottom) at VBC1 center without fringe fields in the DogLeg magnets. Normalized emittance at 95% is 12 mm.mrad.

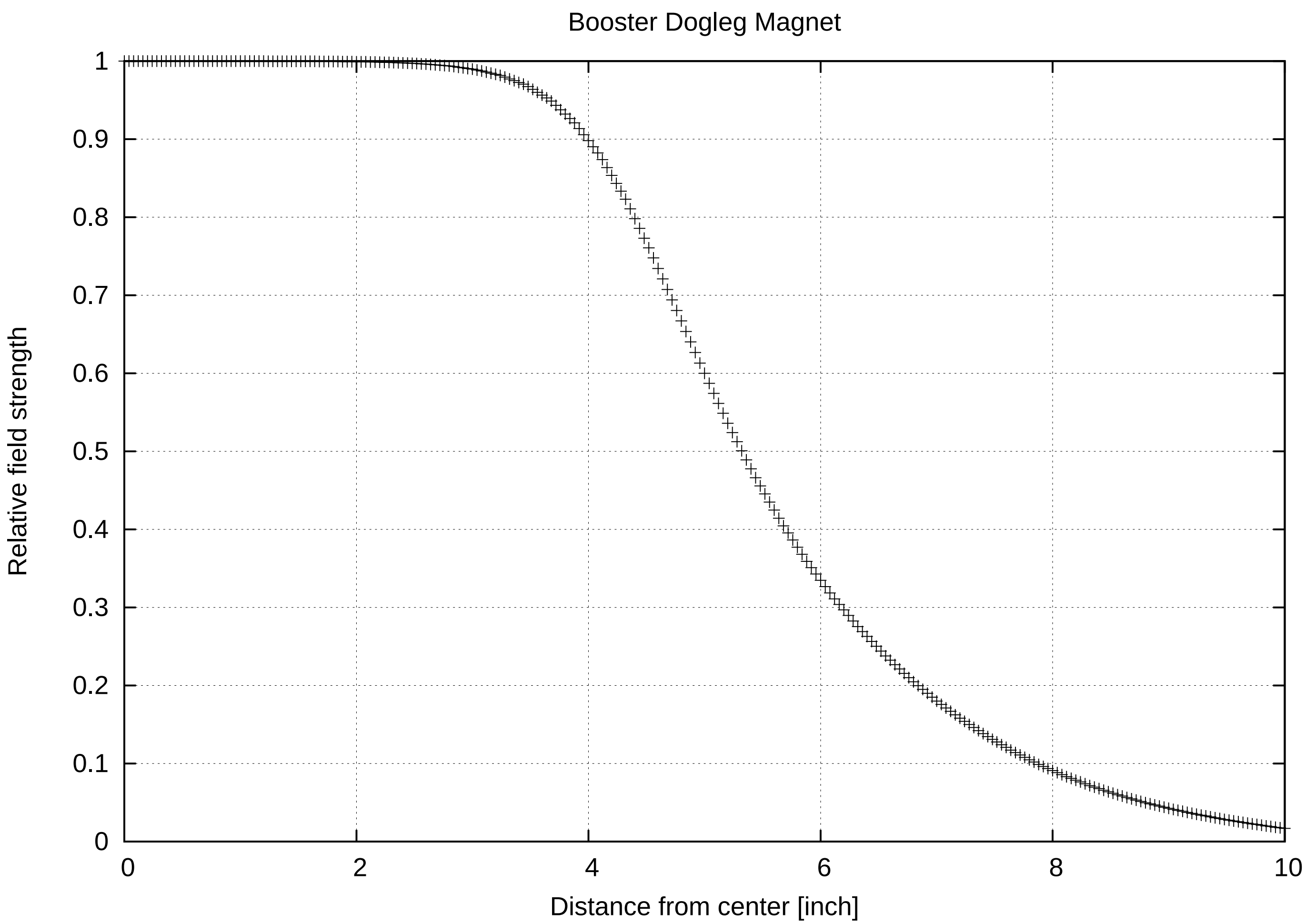


Figure 6: Calculated magnetic field in the medium plane of the Booster DogLeg magnet.

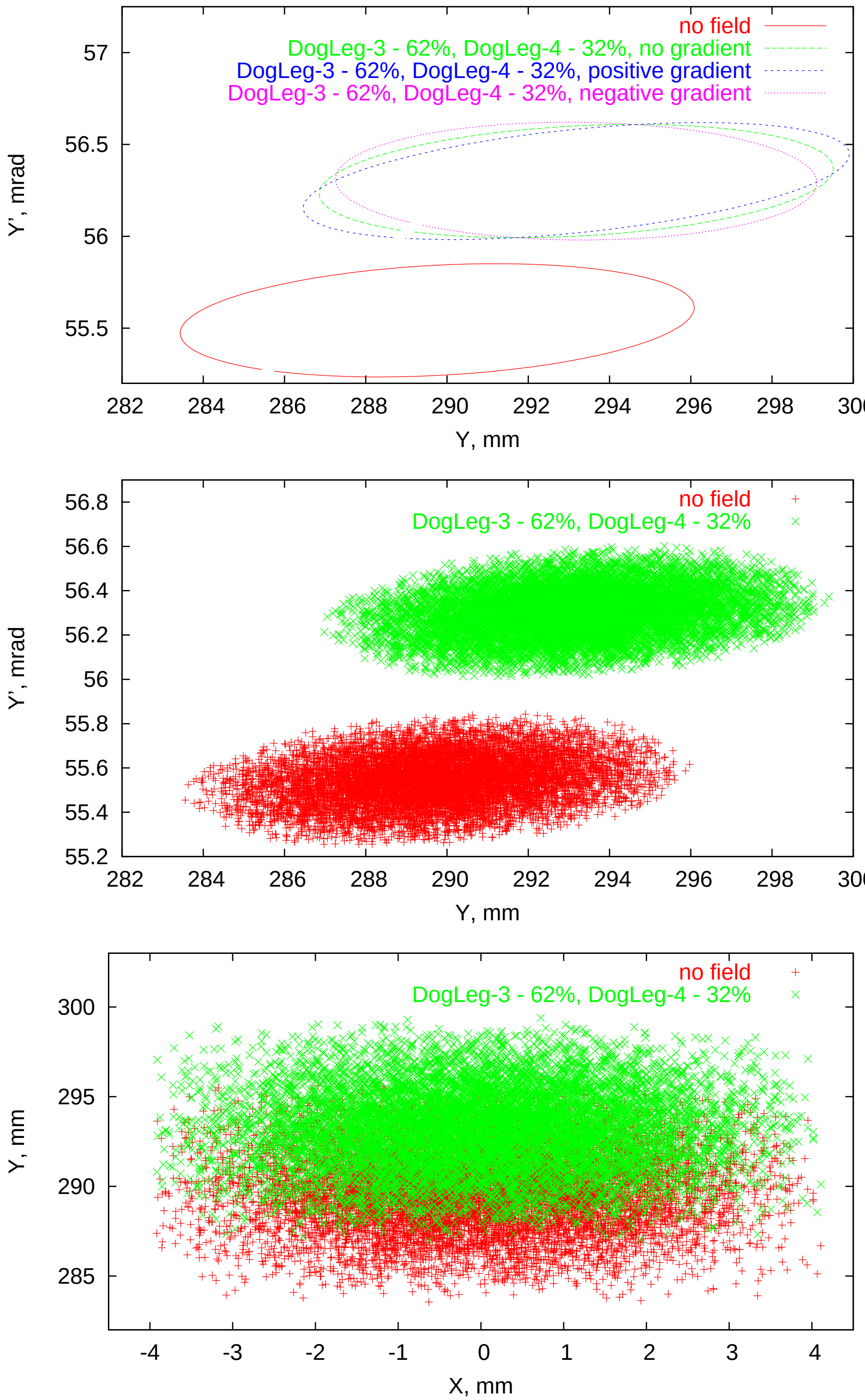


Figure 7: Vertical phase space (top and middle) and beam population (bottom) at VBC1 center for magnetic field of 62% and 32% of the nominal gap field in the DogLeg magnets number 3 and 4 at the extracted beam trajectory. With and without gradient of fringe field in magnets number 3 and 4. The beam displacement at VBC1 center is $\Delta Y = 3.423\,mm,\ \ \Delta Y' = 0.758\,mrad$.

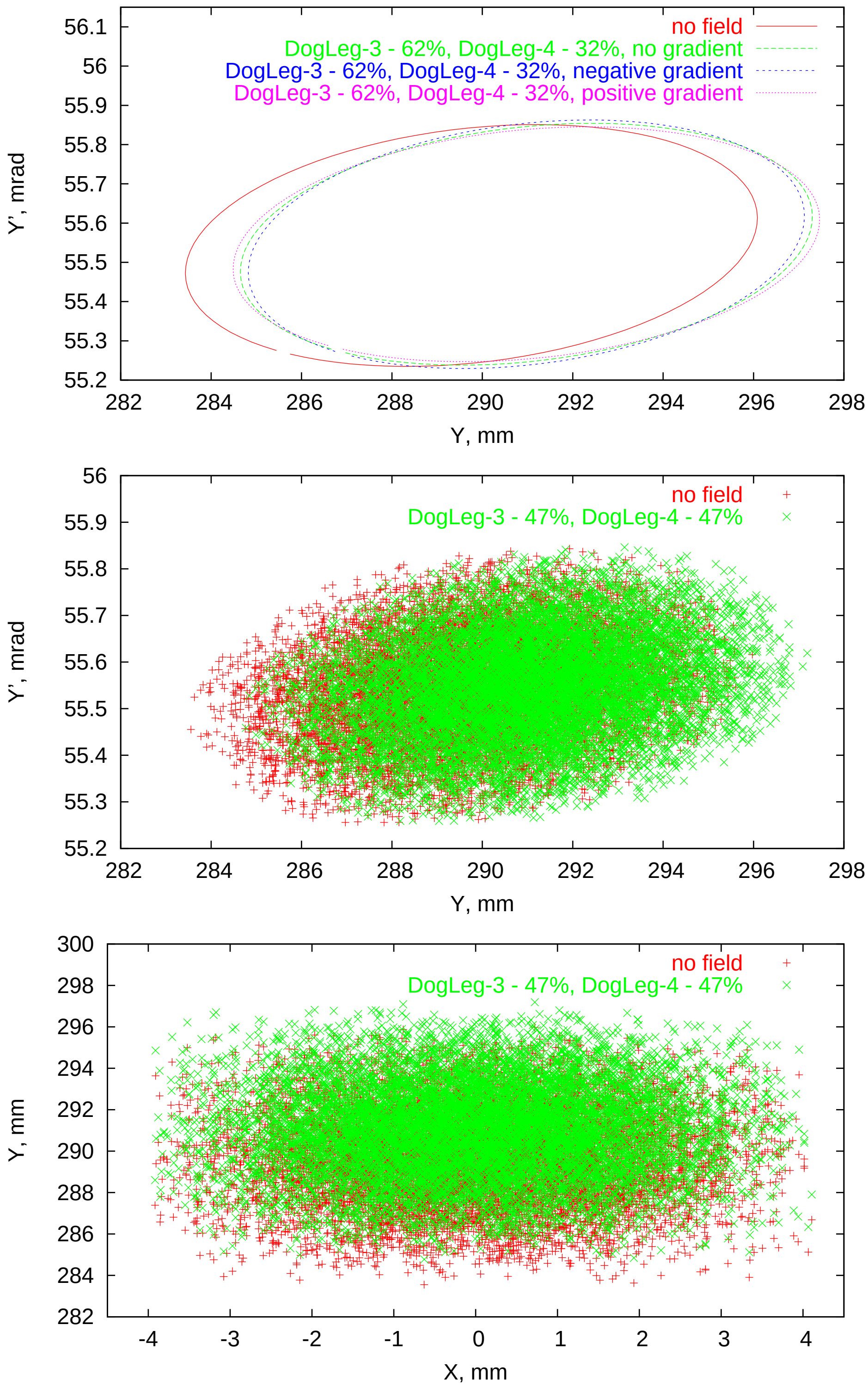


Figure 8: Vertical phase space (top and middle) and beam population (bottom) at VBC1 center for magnetic field of 47% and 47% of the nominal gap field in the DogLeg magnets number 3 and 4 at the extracted beam trajectory. With and without gradient of fringe field in magnets number 3 and 4. The beam displacement at VBC1 center is $\Delta Y = 1.22\, mm, \quad \Delta Y' = 0.0032\, mrad$. An equal field at the extracted beam trajectory can be obtained by displacement of magnet number 3 down and magnet number 4 up by (155.73mm-124.44mm)/2 from the designed position (see Fig. 2).

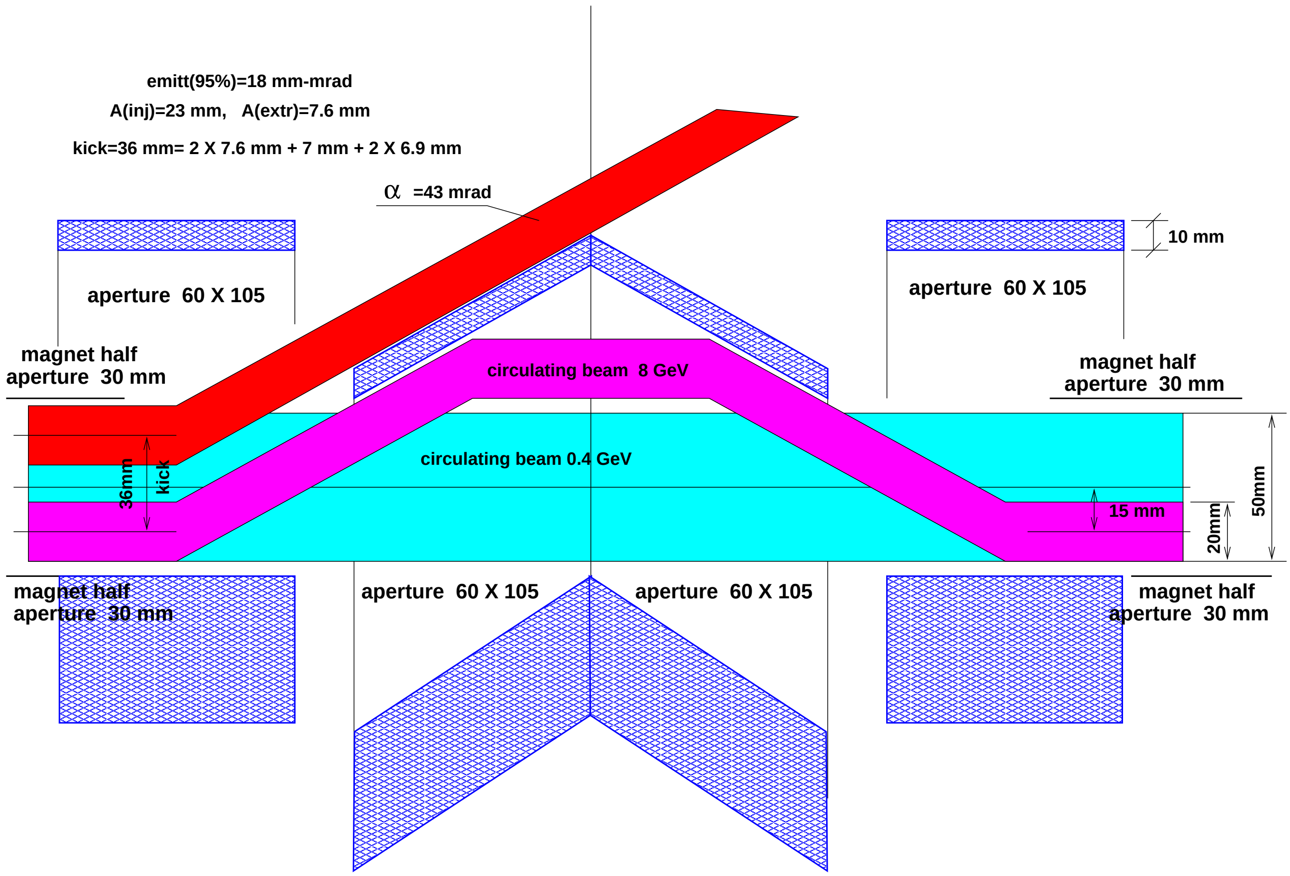


Figure 9: Proposed extraction bump at Long-03 straight section with pulsed bump-septum magnets used only at the top energy. The septa is outside of the main magnet aperture.

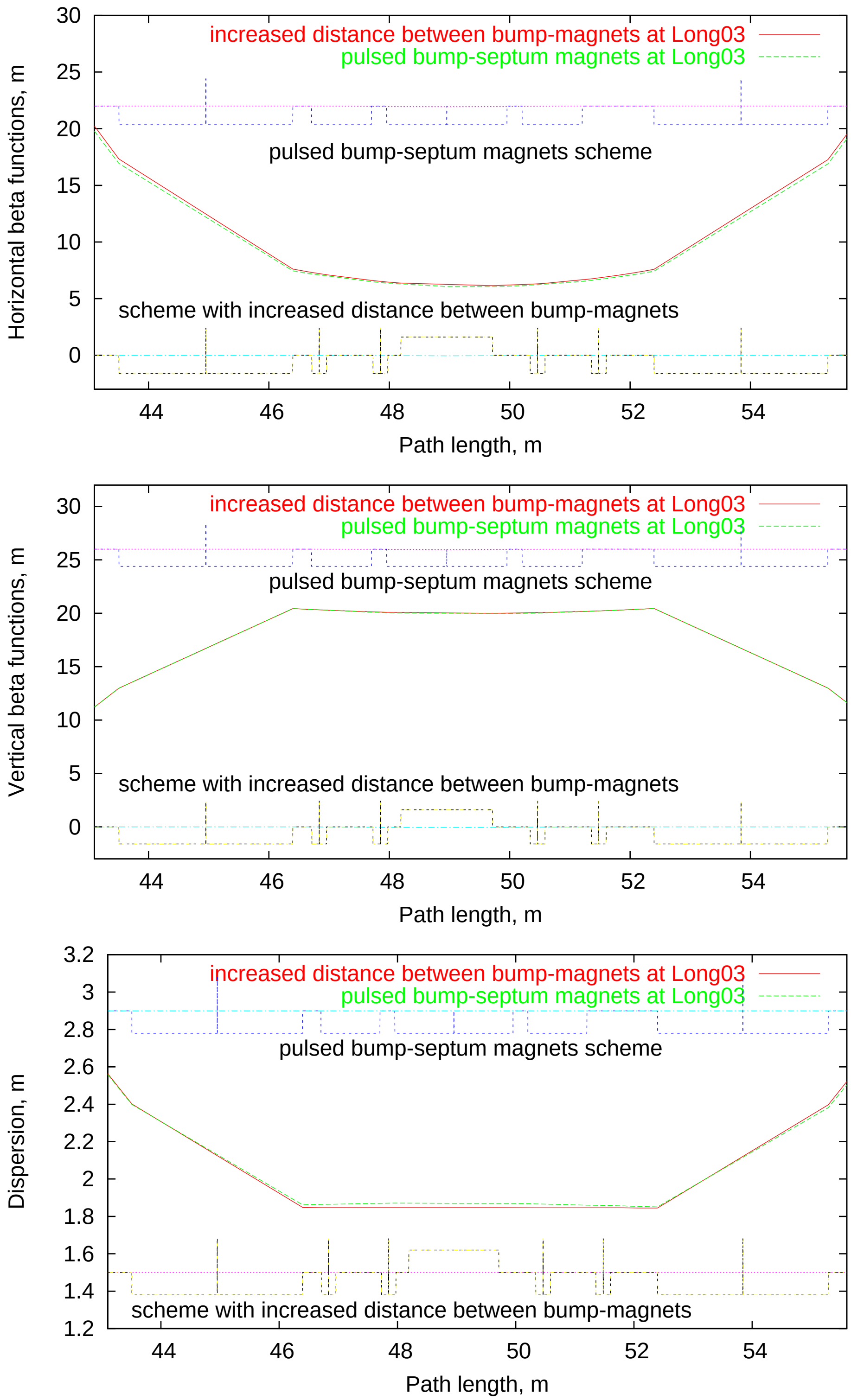


Figure 10: Horizontal and vertical β functions (top) and horizontal dispersion (bottom) at the top energy in the extraction region (Long03) for new extraction bump with increased distance between bump-magnets and for the scheme with pulsed bump-septum magnets used only at the top energy.