Transverse space charge forces in XFEL optics after final compression

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Beam lines:

A. Main linac (max 30 cells):

- 90° cell: XFEL_19NOV04.mad
- 60° cell.

B. Main linac with upstream diagnostic section.

Beam parameters:

- Energy: (0.5 - 3.0) GeV.
- Current: 5 kA.
- Normalized emittance: 1 $mm \cdot mrad$.
- Matched Gaussian beam truncated at $3\,\sigma$.

Acceleration in linac:

- $E_{acc} = 20.27\,MV/m$, on-crest.

2 Definitions

- Statistical emittance:

$$\epsilon_x \;=\; \sqrt{\langle x^2\rangle\,\langle p_x^2\rangle \;-\; \langle x p_x\rangle^2}$$

- Statistical β-function:

$$\beta_x \;=\; \frac{\langle x^2\rangle}{\epsilon_x}$$

- Moment invariant of coupled 2D linear motion (includes linear space charge when treated in the Vlasov approximation) (first discovered by W.Lysenko):

$$I_{xy}^2 \;=\; \frac{\epsilon_x^2 \;+\; \epsilon_y^2 \;+\; 2\cdot(\langle xy\rangle\,\langle p_x p_y\rangle \;-\; \langle x p_y\rangle\,\langle y p_x\rangle)}{2}$$

- Statistical normalized emittance:

$$\epsilon_{x,n} \;=\; \beta_0\gamma_0\epsilon_x$$

where p_x, p_y are particle momentum divided by design momentum.

3 Some tests

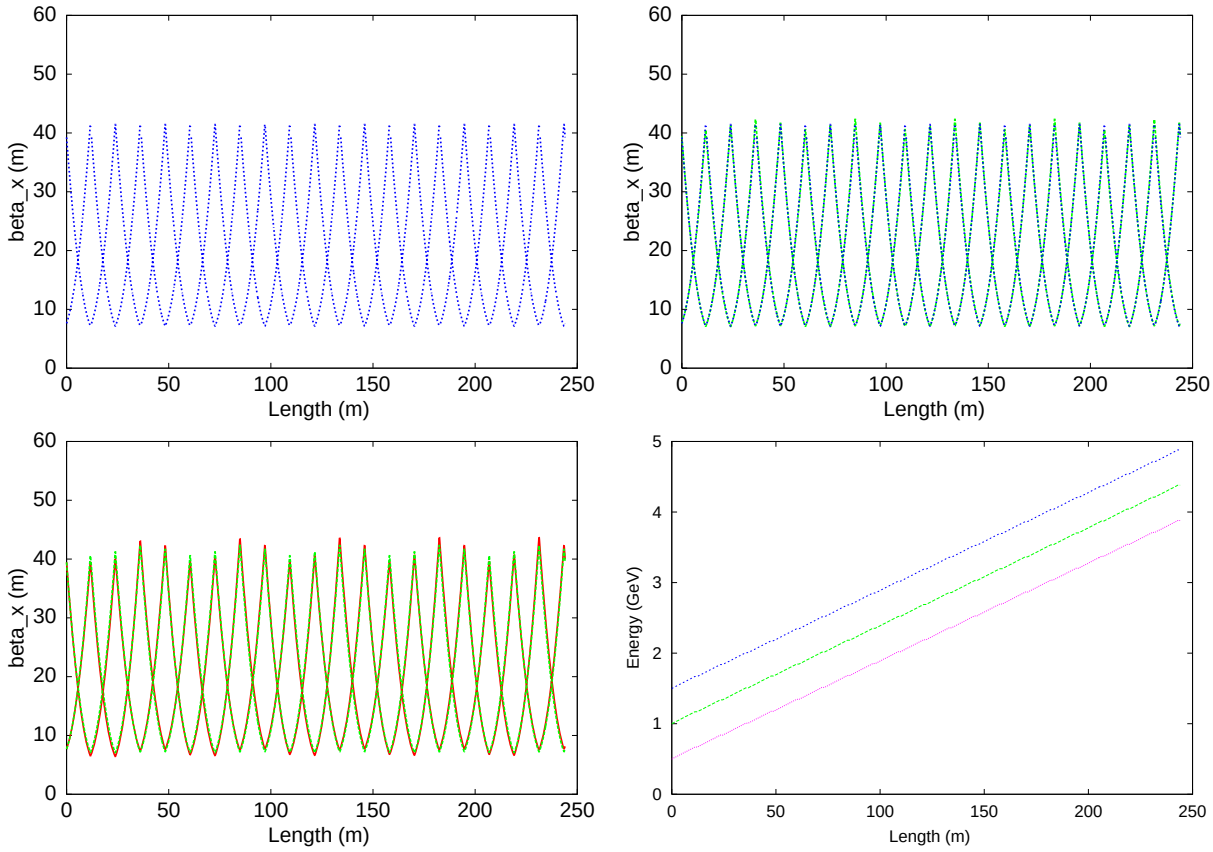

Figure 1: Main linac: 90° cells (10 cells). $I = 0$. Blue: periodic solution without RF cavities. Green: statistical beta functions without RF cavities. Red: statistical beta functions with RF cavities. In two last cases the initial Twiss parameters are periodic solution without RF. Bottom right figure is the energy.

4 Beam parameters: $E = 500\,MeV$.

$\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$.

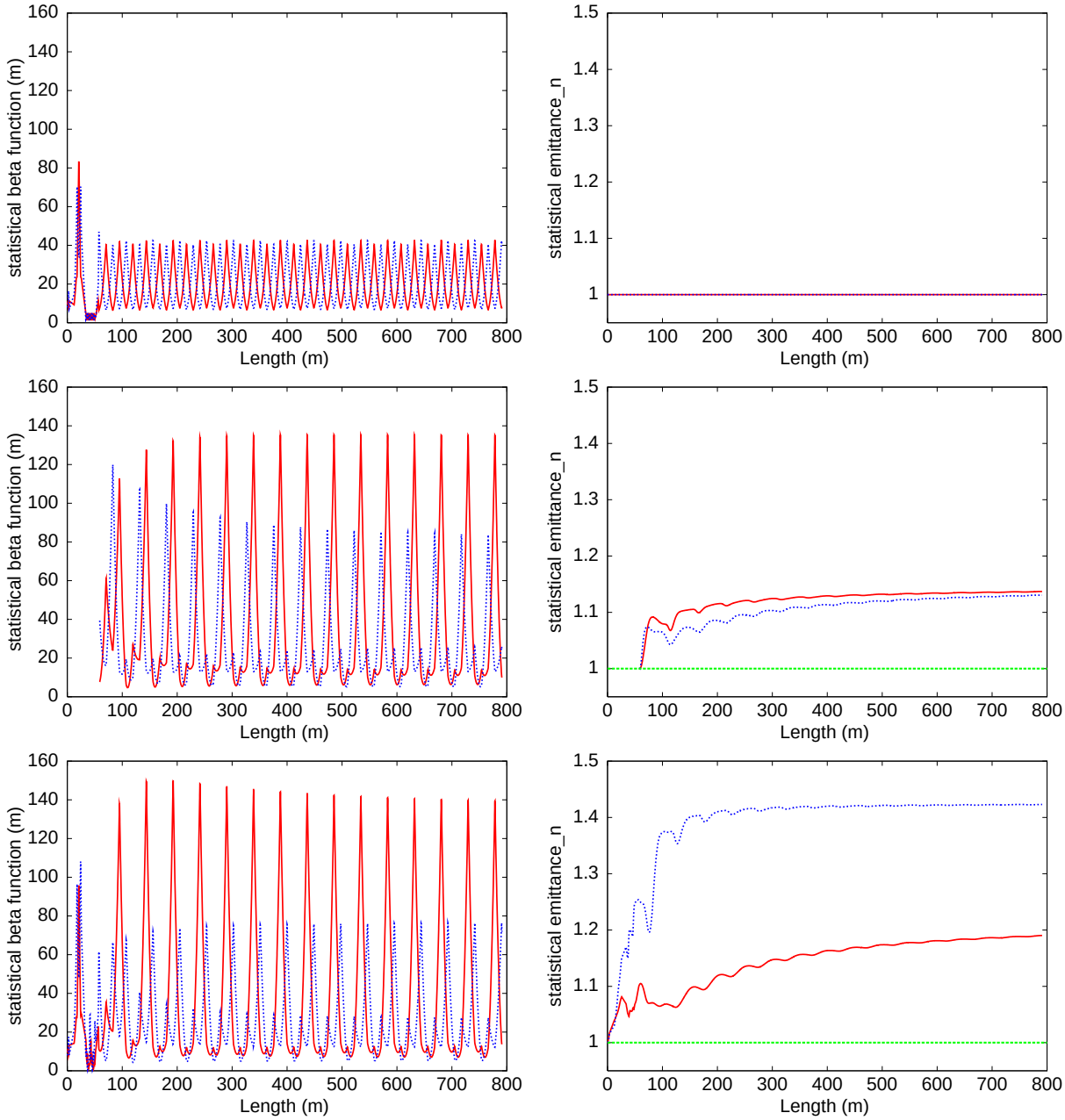

Figure 2: Main linac without (middle) and with (top, bottom) upstream disagnostic section. Beam parameters: $E = 500\,MeV$. $\varepsilon_n = 1\,mm \cdot mrad$. $I = 0$ (top), $5\,kA$ (middle and bottom).

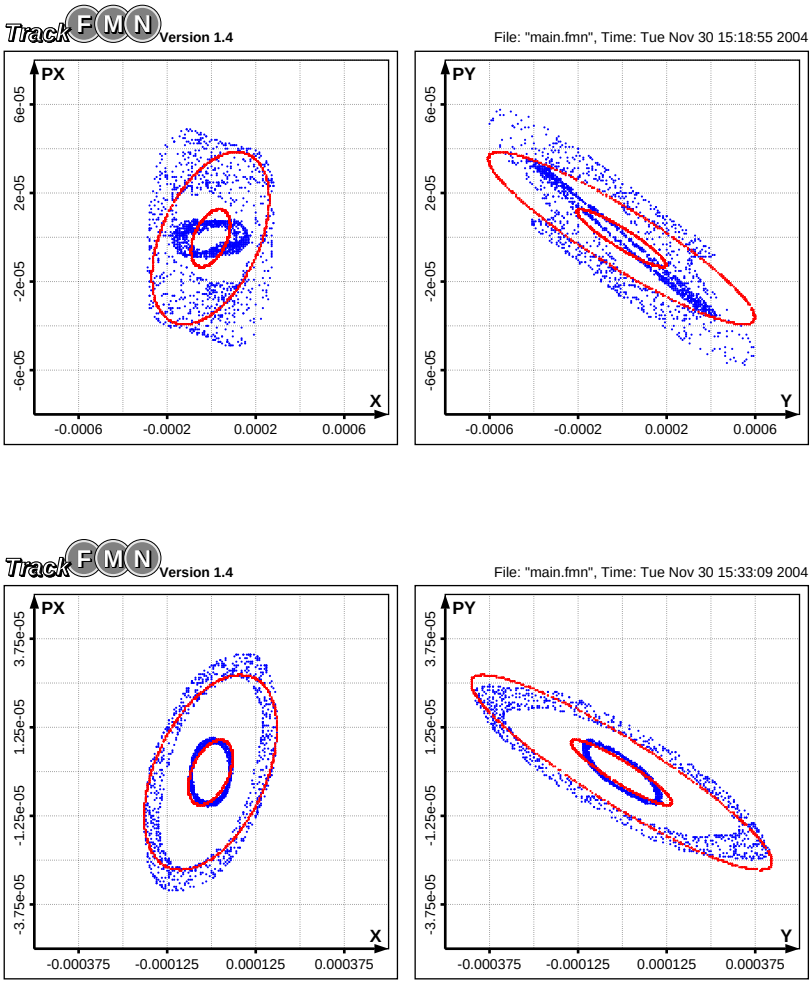

Figure 3: Exit of diagnostic section (linac entrance). Test 1 σ and 3 σ particles (which feel the space charge forces of main particles but not contribute in these forces). $\varepsilon_n = 1\,mm \cdot mrad$. $I = 0$ (red), 5 (blue) kA. $E = 500$ MeV (top), 1 GeV (bottom).

5 Main Linac (90° cell): initial energy (0.5 - 3) GeV

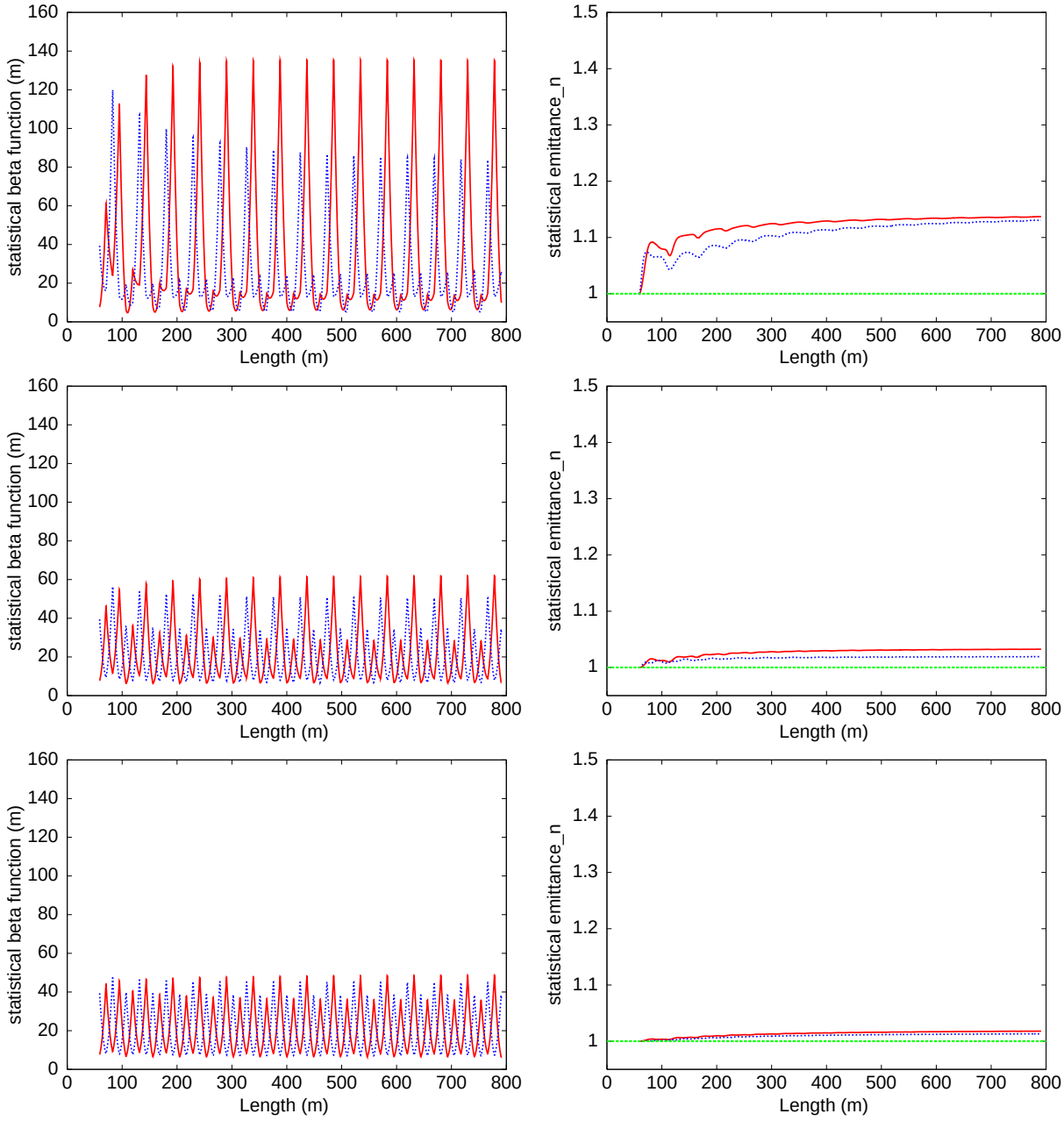

Figure 4: Main linac (90° cell, 30 cells). $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. Initial energy: $E = 0.5$, 1.0, 1.5 GeV (from top to bottom).

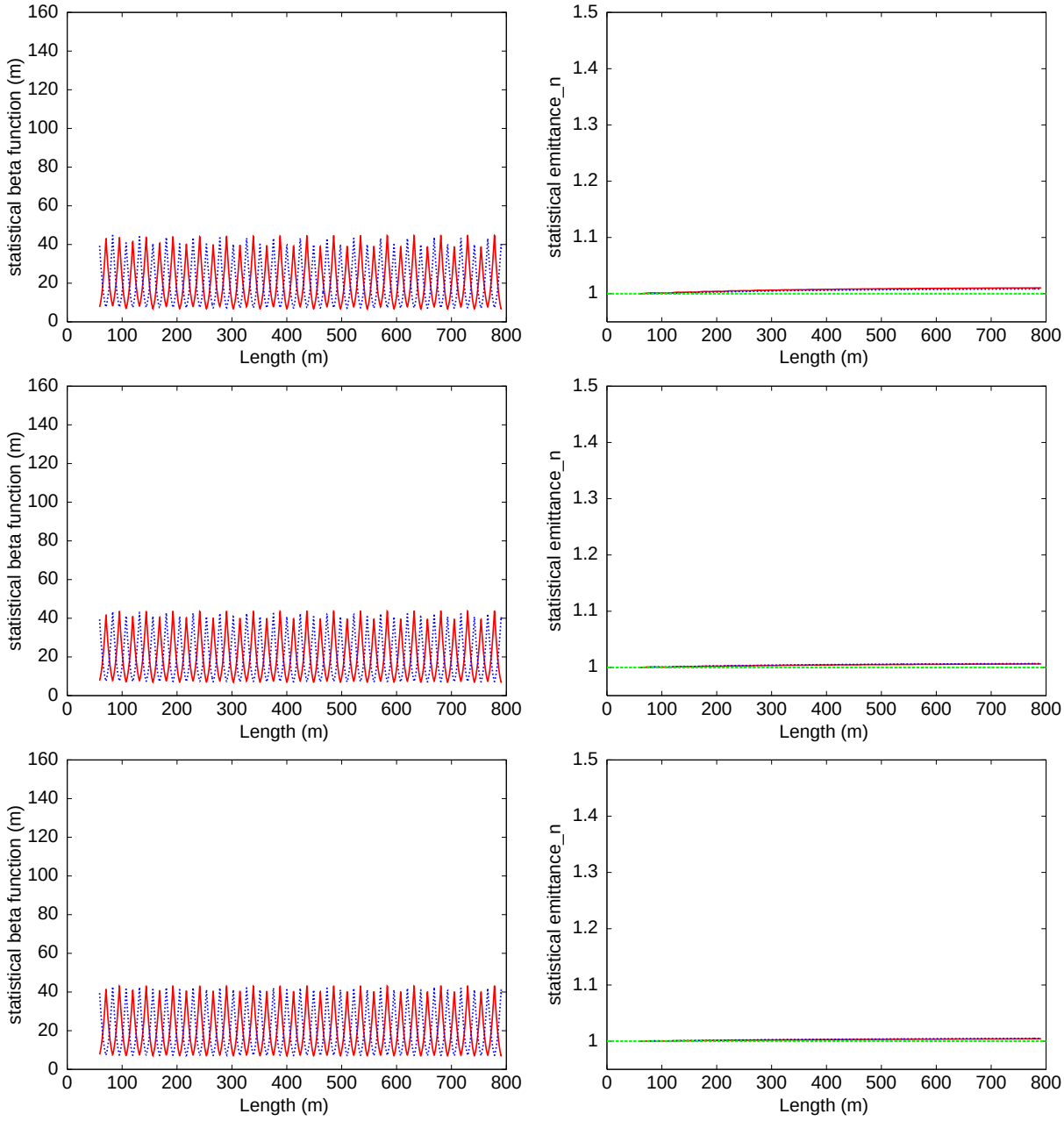

Figure 5: Main linac (90° cell, 30 cells). $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. Initial energy: $E = 2.0, 2.5, 3.0$ GeV (from top to bottom).

6 Linac with upstream diagnostic section (90° cell): initial energy (0.5 - 3) GeV

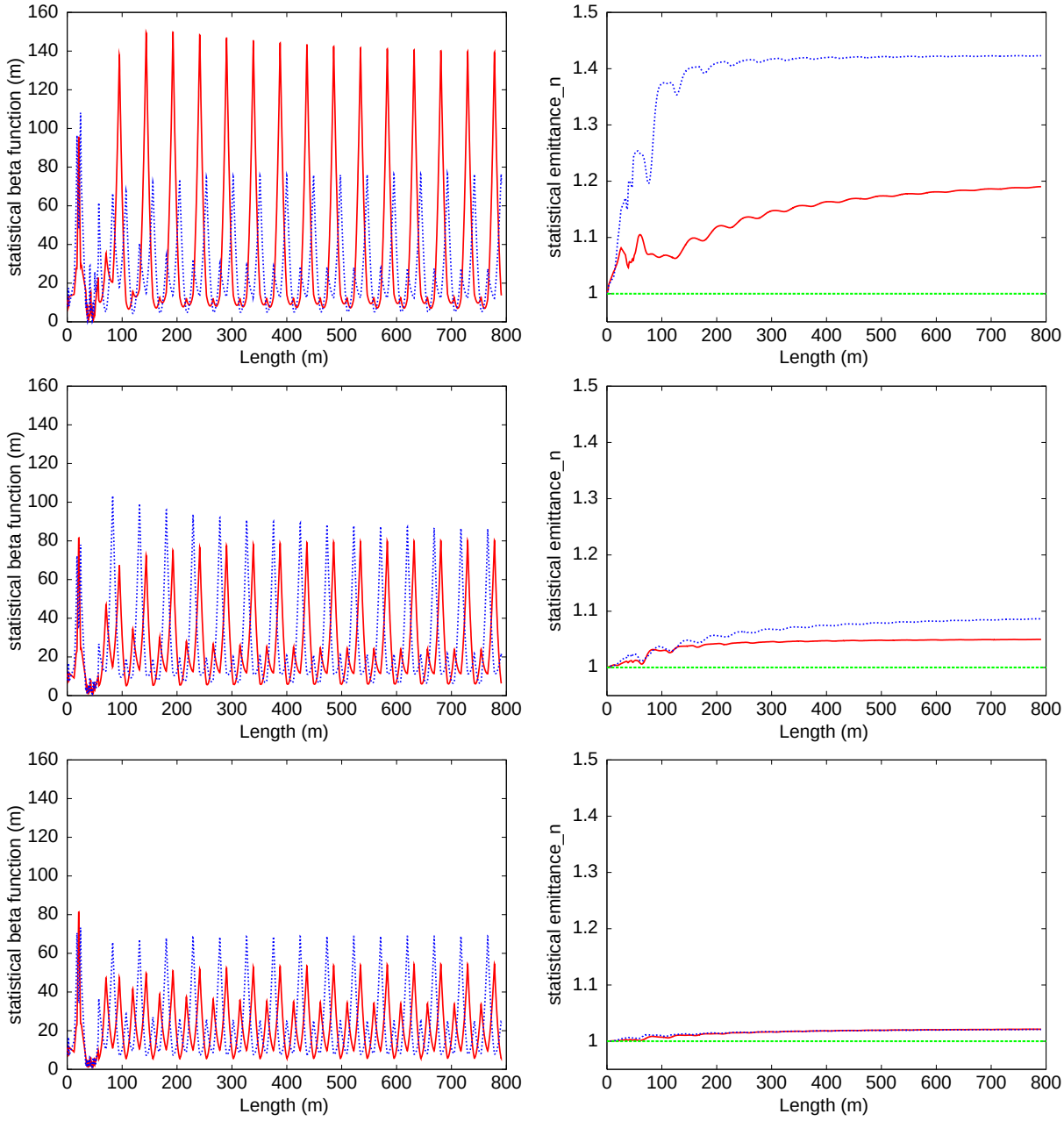

Figure 6: Main linac with upstream disagnostic section. $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. Initial energy: $E = 0.5$, 1.0, 1.5 GeV (from top to bottom).

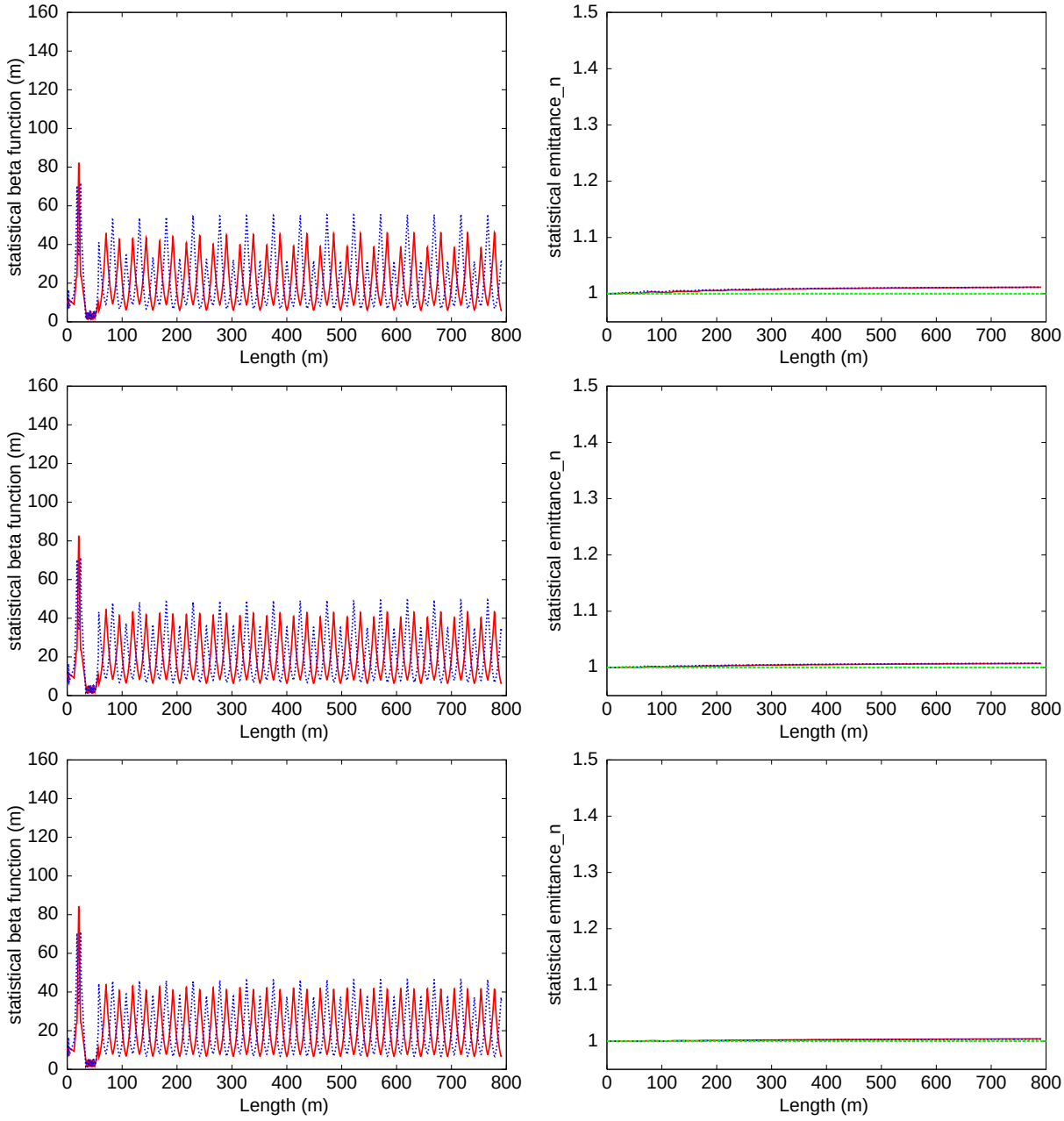

Figure 7: Main linac with upstream disagnostic section. $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. Initial energy: $E = 2.0, 2.5, 3.0$ GeV (from top to bottom).

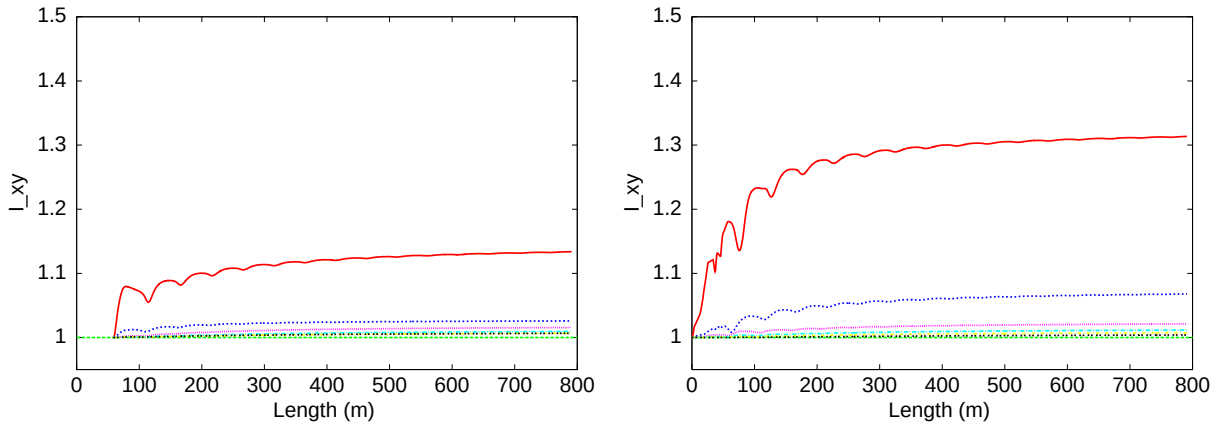

Figure 8: Moment invariants (divided by their initial values and multiplied by $\gamma(z)$). $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. $E = (0.5 - 3.0)\,GeV$ (from top to bottom with 0.5 GeV step). Right: linac (90°, 30 cells). Left: linac with upstream diagnostic section.

6.1 Main Linac: 60° cell

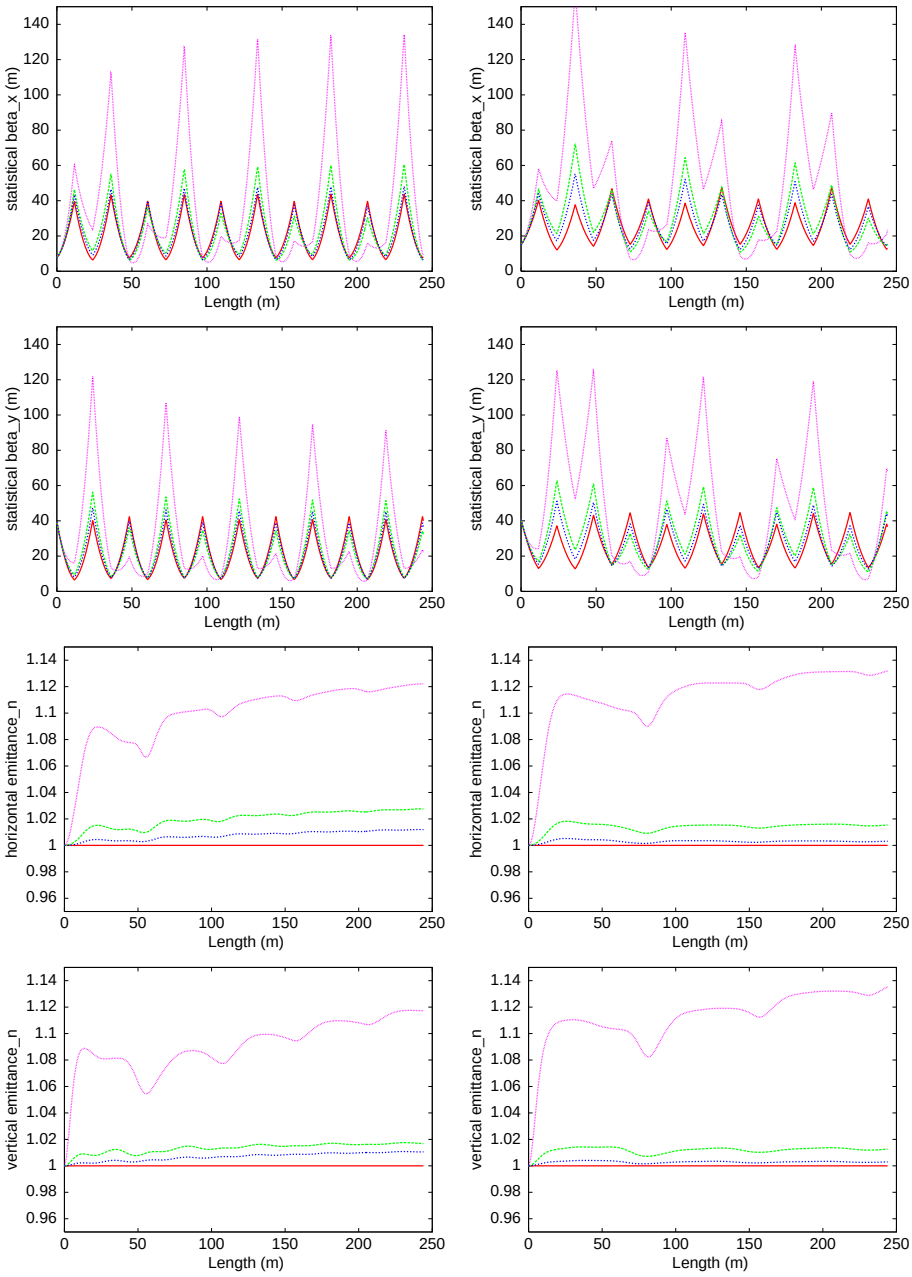

Figure 9: Main linac: 90° (left) and 60° (right) cells (10 cells). $\varepsilon_n = 1\,mm \cdot mrad$. $I = 5\,kA$. Initial energy: $E =$ 0.5 (magenta), 1 (green), 1.5 (blue) GeV. Red: $I = 0$.

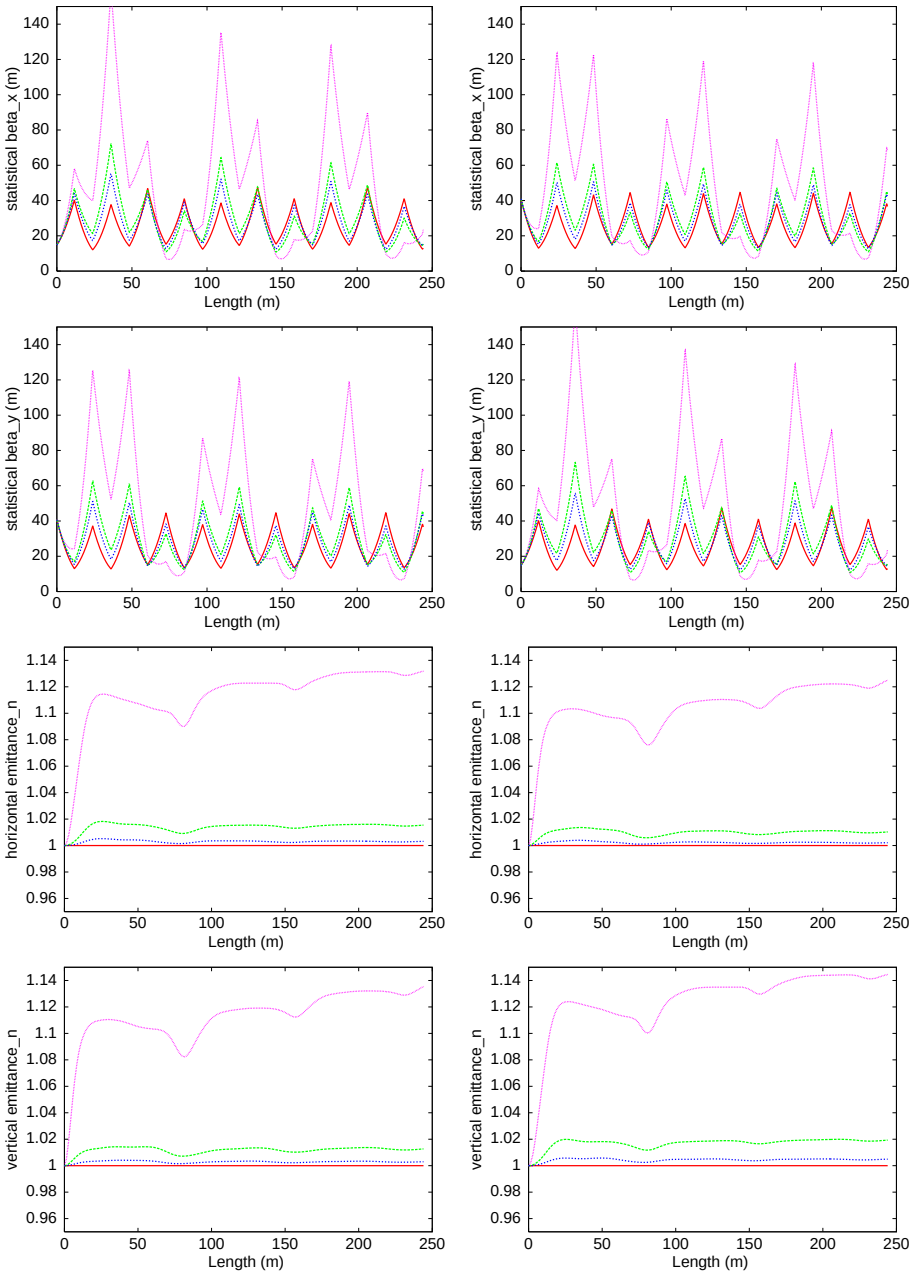

Figure 10: Main linac: 60° cell: FODO (left) and DOFO (right) (10 cells). $\varepsilon_n = 1\,mm\cdot mrad$. $I = 5\,kA$. Initial energy: $E = 0.5$ (magenta), 1 (green), 1.5 (blue) GeV. Red: $I = 0$.