Electron beam transverse focusing for self-modulation studies at PITZ

22MeV electron beam transverse focusing at the entrance (at the middle) of the plasma cell by using:

Two quadrupoles in the High section → High1 (Q1+Q2)

Four quadrupoles in the High section High1 (Q1+Q2+Q3+Q4)

Summary of beam parameters for 18, 22 and 25 MeV cases

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DESY

Goal and parameters for ASTRA simulations

Requirements for an electron beam with 100pC charge:

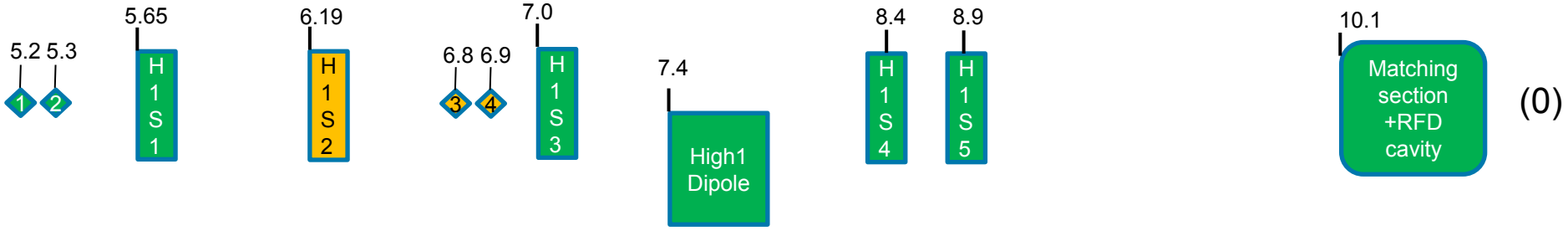
- Smooth beam transverse focusing at the entrance / middle of plasma cell (z = [6.4-6.5] m)
- Transverse beam rms size → $\sigma_{xy} = \sqrt{\sigma_x \cdot \sigma_y} \sim 50\,\mu m$

Setup for beam simulations

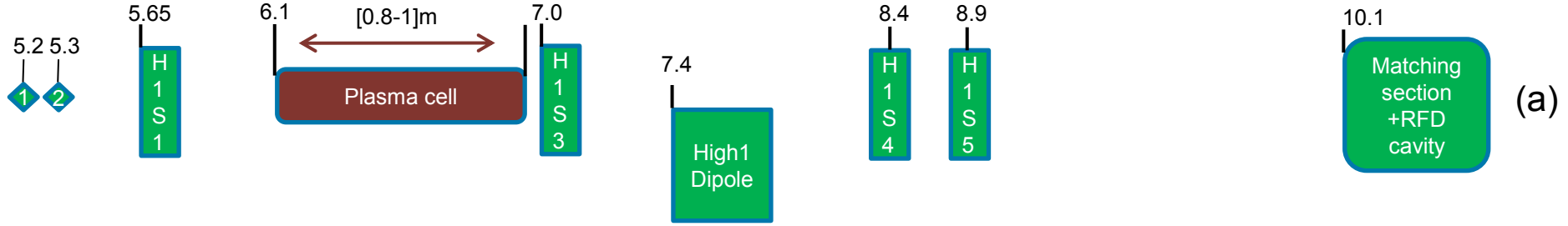
- Laser: Longitudinally flat-top → 2/22\2 ps. Transverse rms spot size on the cathode → 0.3mm
- Gun: Gradient of 61 MV/m (6.73 MeV/c after gun at on-crest phase), phase fixed to on-crest
- Booster: Gradient of 17.5 MV/m (22 MeV/c final beam momentum for gun and booster on-crest phases), phase fixed to on-crest
- Solenoid scan for e-beam focus on EMSY1
- High.1Q1, High.1Q2, High.1Q3 and High.1Q4 are used for further beam transverse focusing
- 0.5 million macro particles in ASTRA resulting 100pC charge

Beam focusing scenarios with and without H1.Q3 and H1.Q4

Current PITZ beamline after the booster and before the matching section (beam direction from left to right).



PITZ beamline with plasma cell → H1.S2 is removed, Q3, Q4 are also removed.



PITZ beamline with plasma cell → H1.S2 is removed, Q3, Q4 right after H1S1.

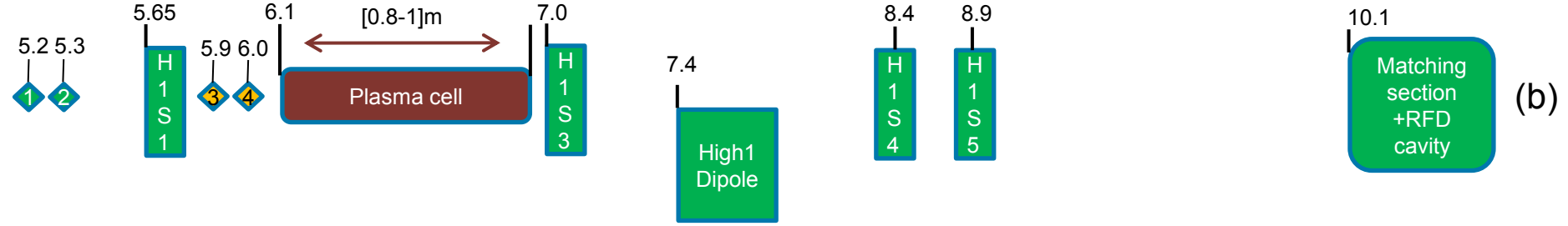


Fig.1. Beam transverse focusing scenarios.

Beam focusing on EMSY1 by the main solenoid (no quads)

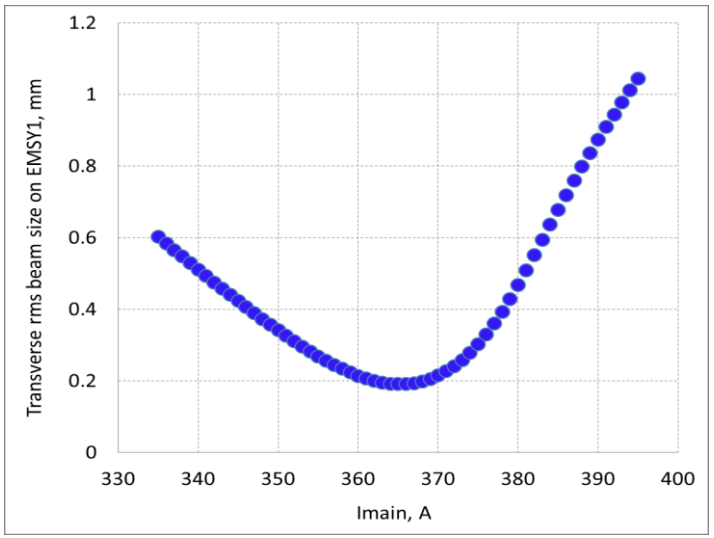
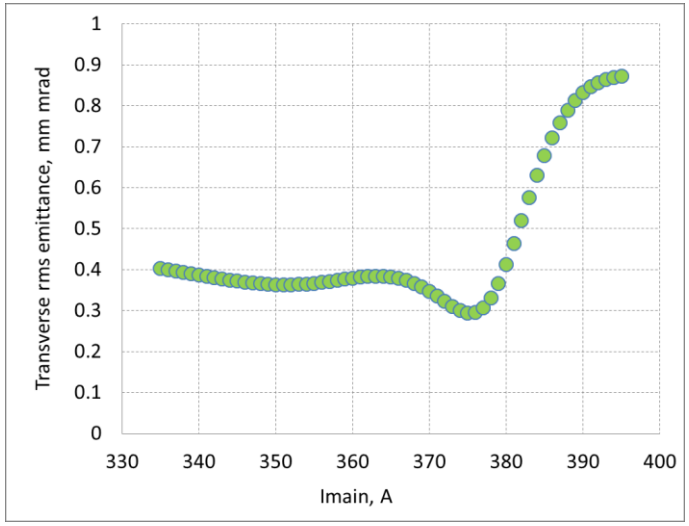


Fig.2. Transverse rms beam size and emittance at EMSY1 vs. Imain.



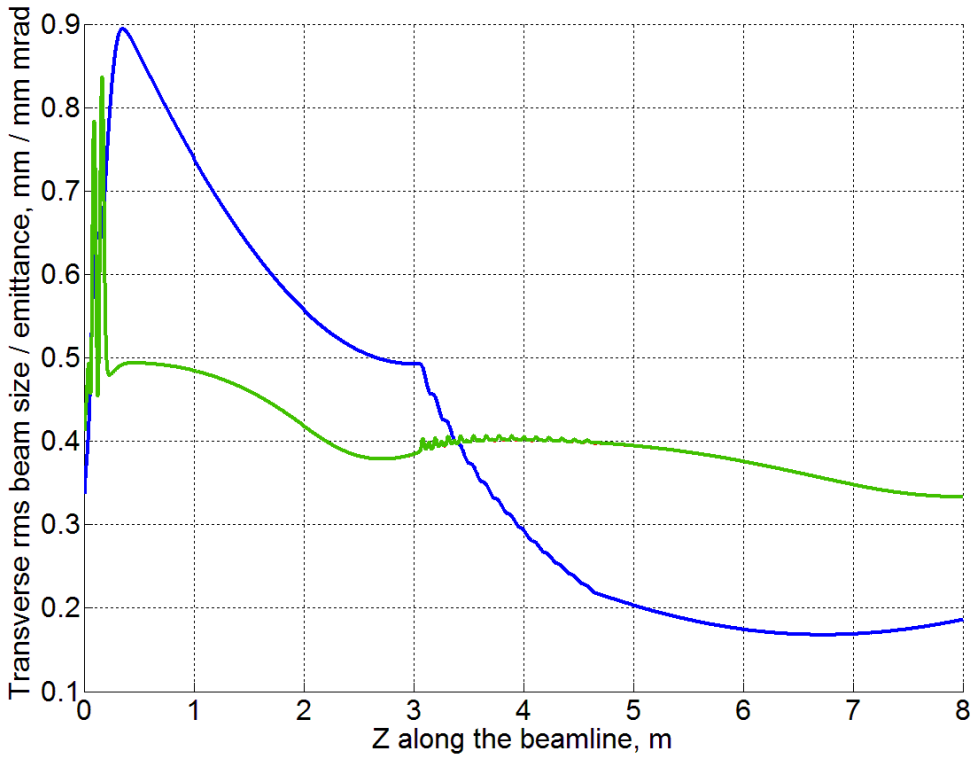


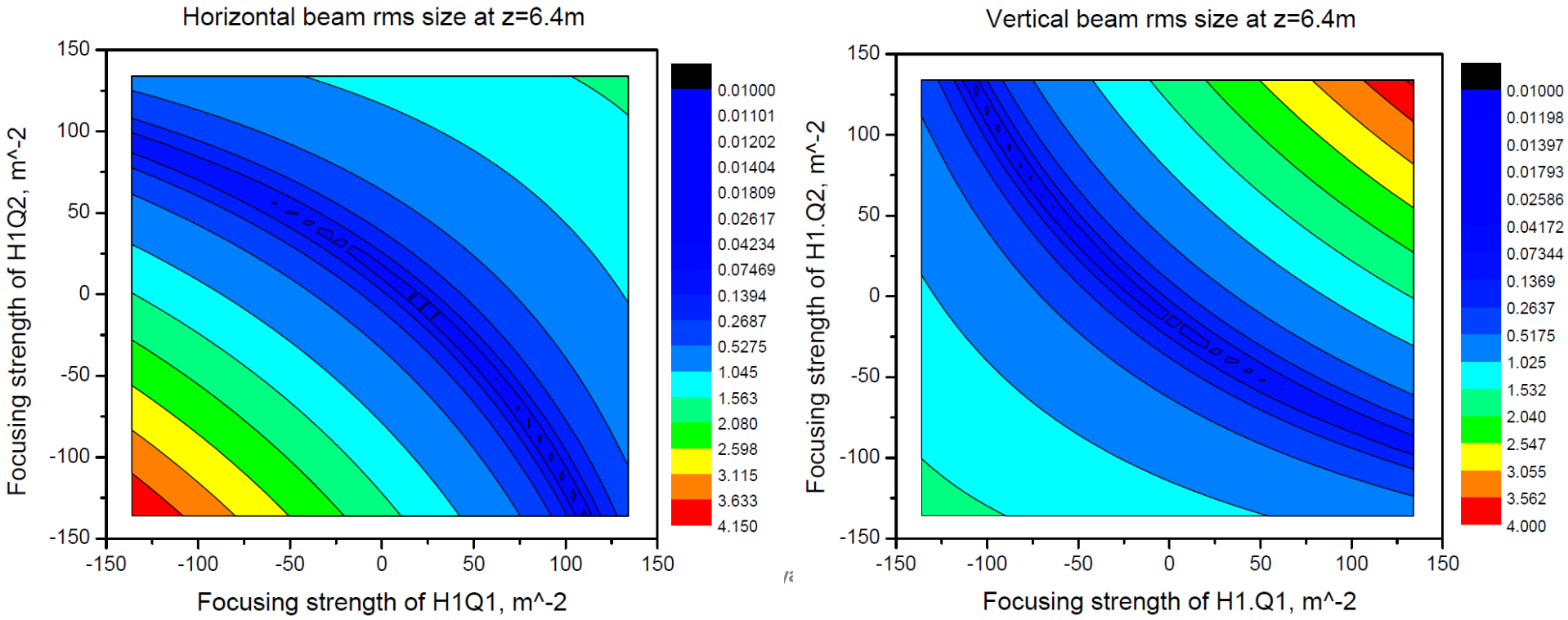
Fig.3. Transverse rms beam size and emittance along PITZ beamline for Imain=365A.

2D map of the beam transverse size: setup (a) is applied

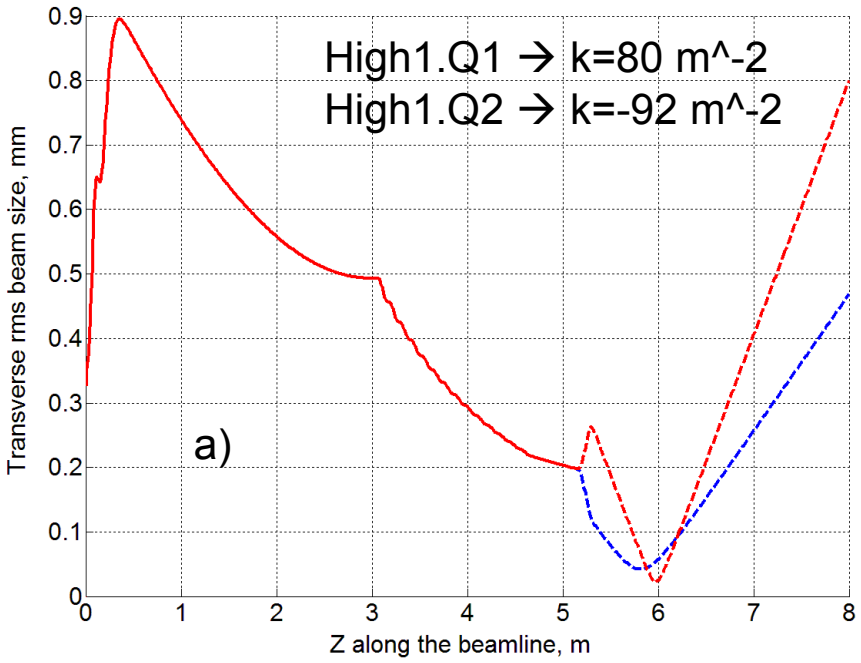
High1.Q1 → position 5.19m (from cathode), L=0.043m, focusing strength → [-136:6:134] m^-2
High1.Q2 → position 5.19m (from cathode), L=0.043m, focusing strength → [-136:6:134] m^-2

Aim →
- a. to have minimum difference between horizontal and vertical beam rms sizes
- b. to get beam size values as small as possible

Fig.4. Transverse beam size at 5.9m for different combinations of H1.Q1 and H1.Q2.



Transverse beam size along beamline: setup (a)



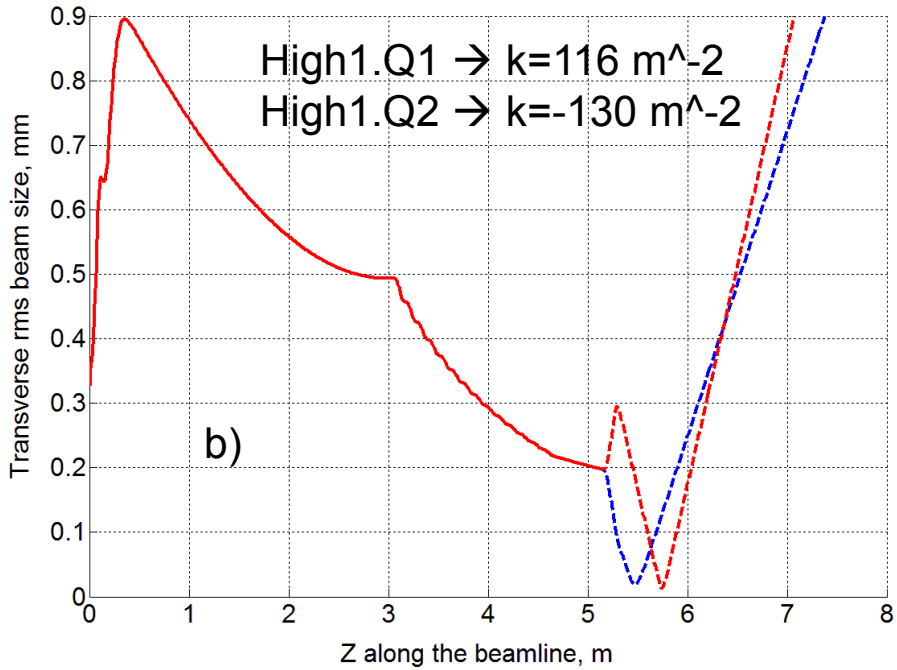


Fig.5. Beam transverse size before and after the quadrupoles for:
a) round beam with the smallest size at 5.9m
b) round beam with the smallest size at 6.4m

It seems that beam focusing with two quadrupoles will not work out !

Beam transverse focusing with setup (b)

Setup for beam simulations

- Laser: Longitudinally flat-top → 2/22\2 ps. Transverse rms spot size on the cathode → 0.3mm
- Gun: Gradient of 61 MV/m (6.73 MeV/c after gun at on-crest phase), phase fixed to on-crest
- Booster: Gradient of 17.5 MV/m (22 MeV/c final beam momentum for gun and booster on-crest phases), phase fixed to on-crest
- Solenoid current for e-beam focus on EMSY1
- High.1Q1, High.1Q2, High.1Q3 and High.1Q4 are used for further beam transverse focusing:
- High1.Q1 → position 5.19m (from cathode), L=0.043m, focusing strength → k = - 46 m^-2 (g [T/m]=-3.38)
- High1.Q2 → position 5.29m (from cathode), L=0.043m, focusing strength → k = 60 m^-2 (g [T/m]=4.409)
- High1.Q3 → position 5.9m (from cathode), L=0.043m, focusing strength → k = - 75.5 m^-2 (g [T/m]=-5.548)
- High1.Q4 → position 6.0m (from cathode), L=0.043m, focusing strength → k = 65.5 m^-2 (g [T/m]=4.813)
- Quad optimization was done by MAD
- 0.5 million macro particles in ASTRA resulting 100pC charge

Transverse beam size along beamline: setup (b)

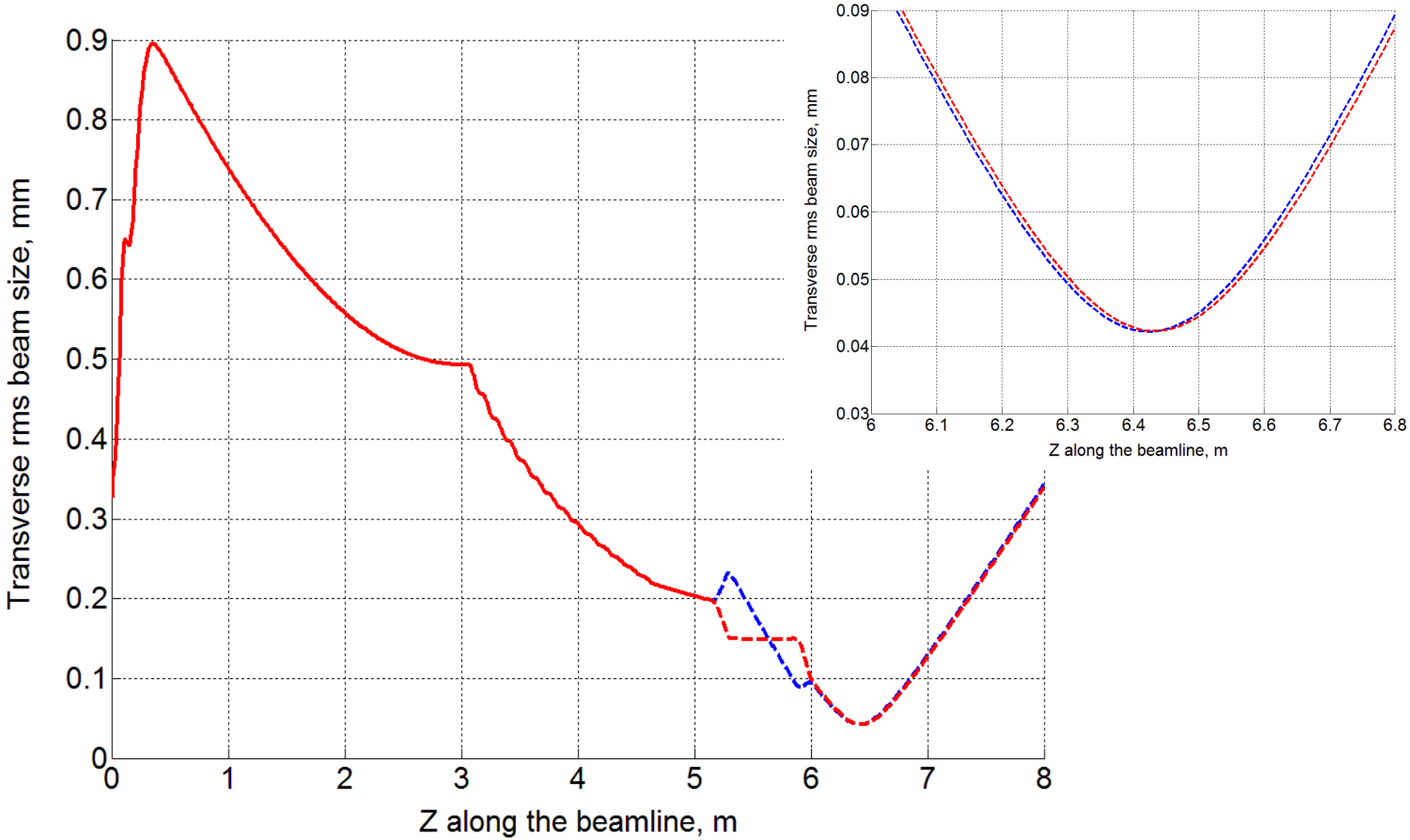


Fig.6. Beam transverse size before and after quadrupole focusing.

Transverse beam emittance along beamline: setup (b)

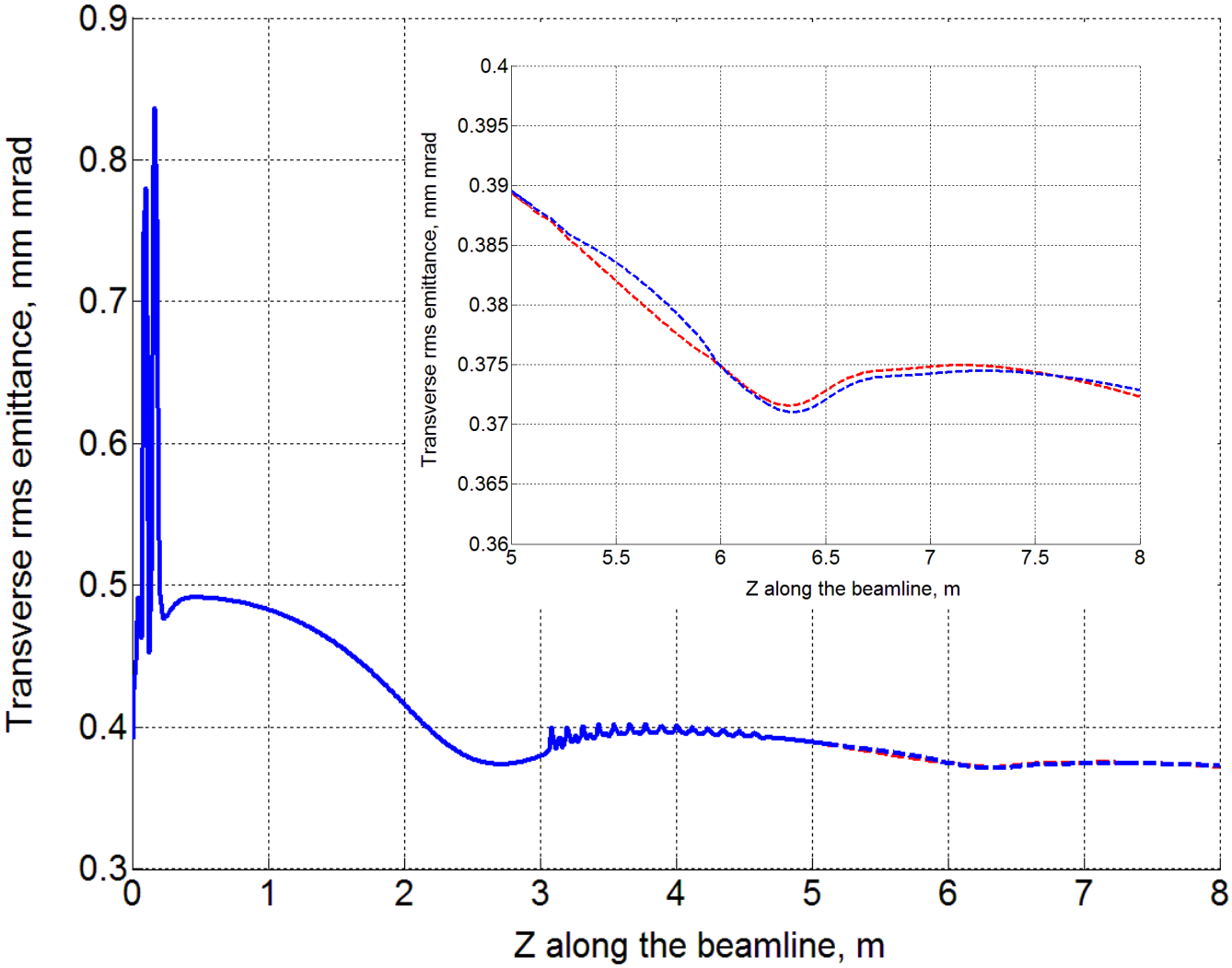


Fig.7. Beam transverse emittance before and after quadrupole focusing.

Beam properties at 6.39m after the cathode: setup (b)

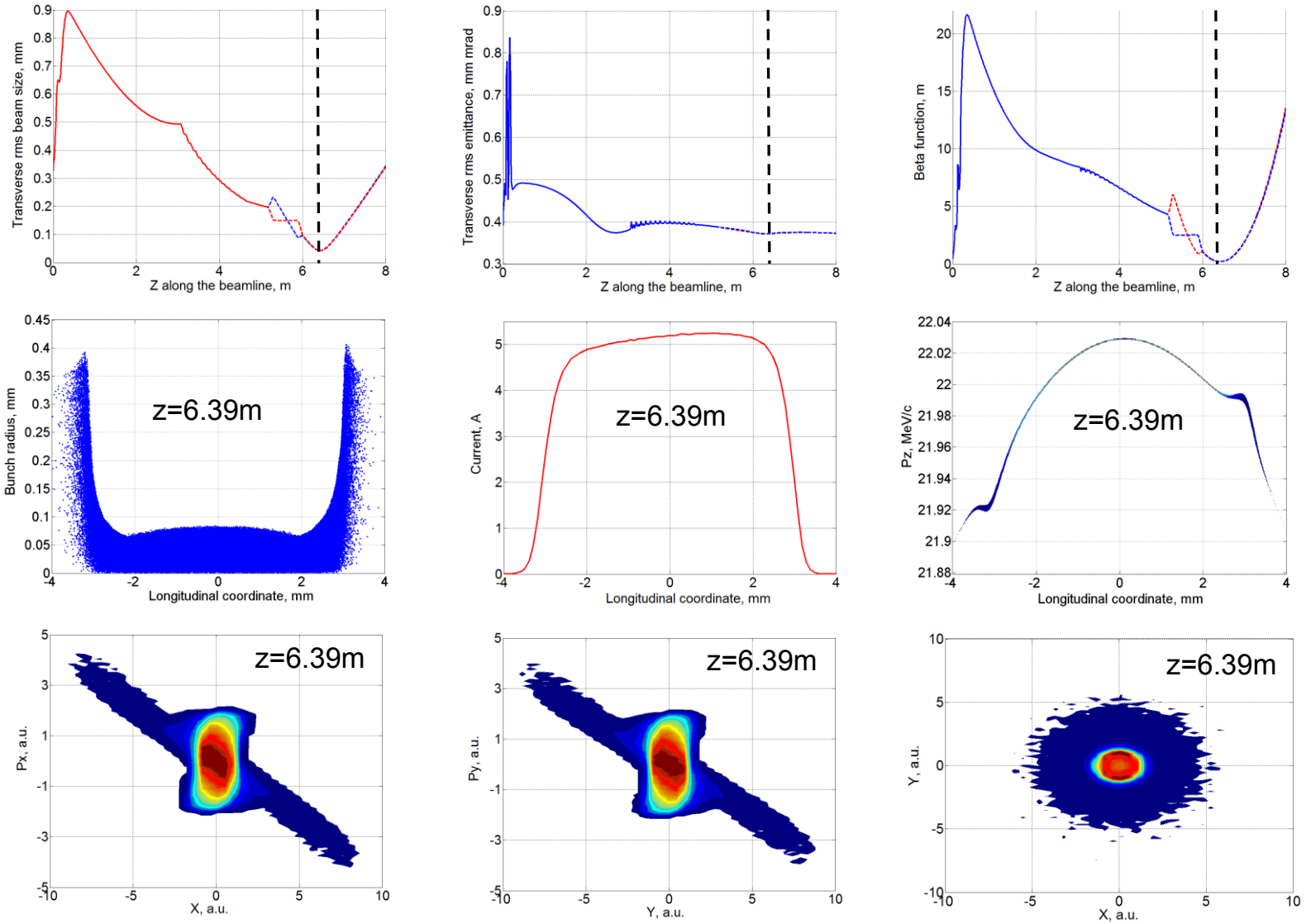


Fig.8. Transverse beam properties along the beamline + beam overview at 6.39m.

Beam properties at 6.44m after the cathode: setup (b)

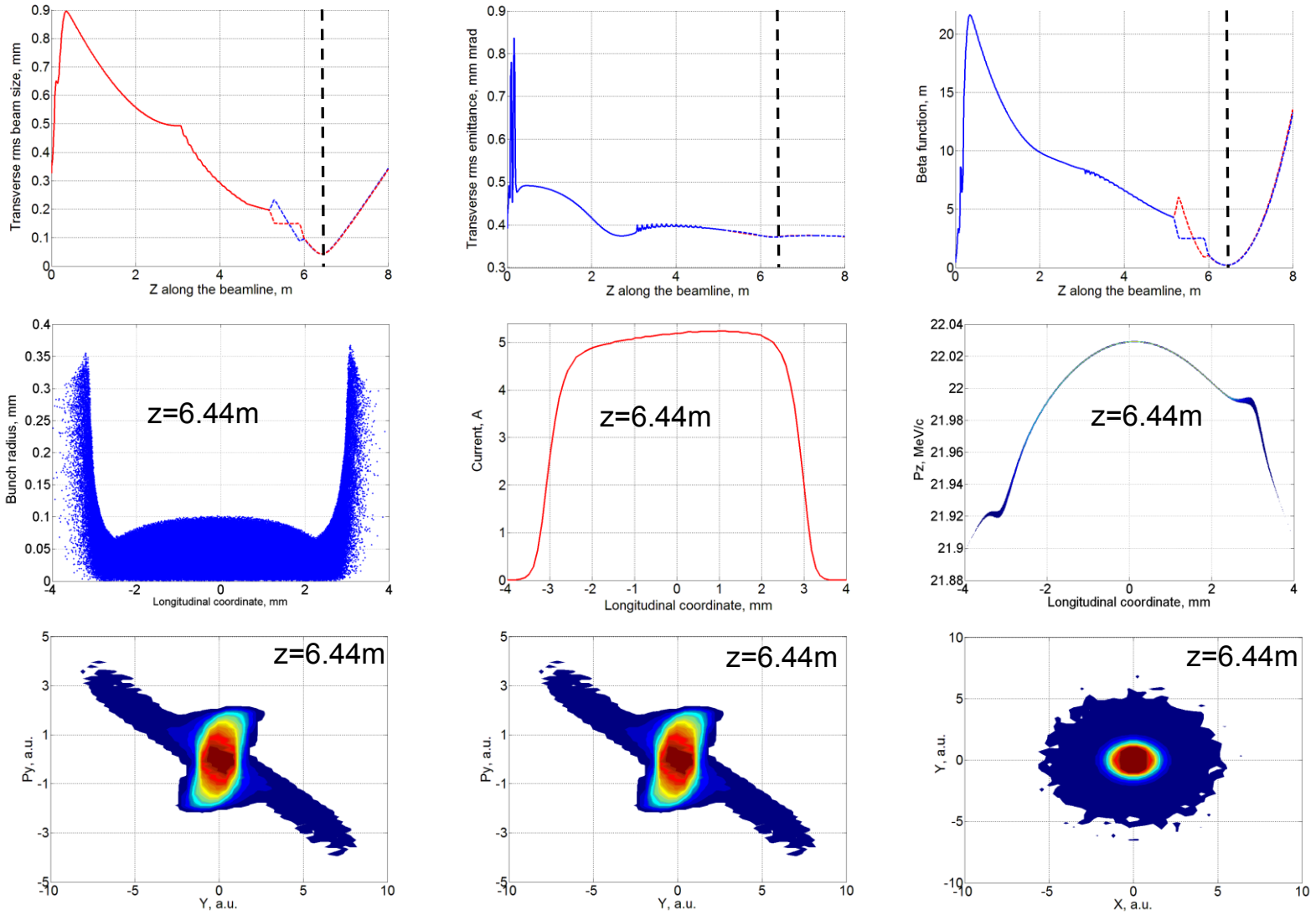
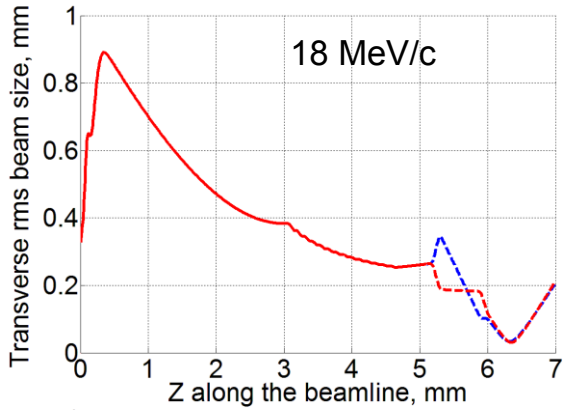
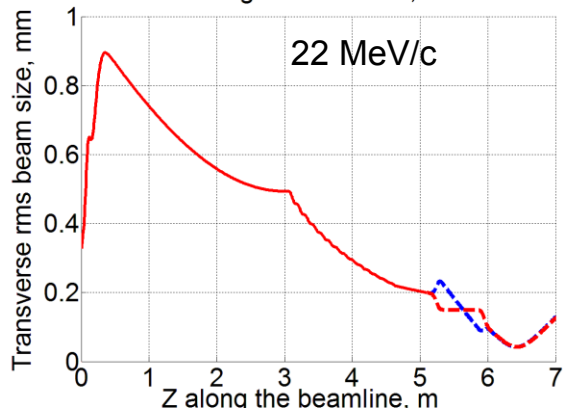
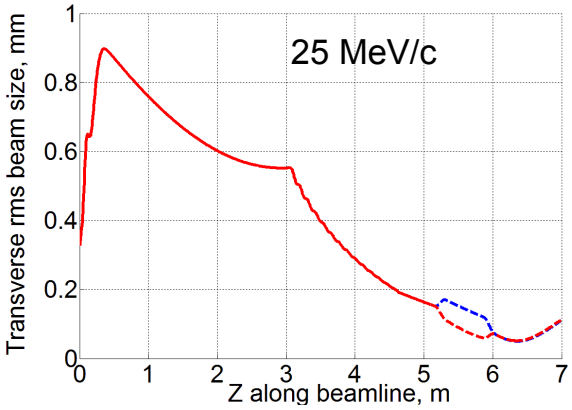


Fig.8. Transverse beam properties along the beamline + beam overview at 6.44m.

Electron beam parameters before entering the plasma for different final beam energies







Beam parameters	Value	Value	Value
Final beam momentum, MeV/c	18.1	22	25
Total charge, pC	100	100	100
Longitudinal beam position, m	6.3	6.44	6.35
Horizontal beam rms size, um	34.3	42	49.8
Vertical beam rms size, mm	34.6	42	51.2
Bunch length in FWHM, mm	5.93	5.93	5.92
Final beam energy, MeV	17.6	21.5	24.55
Peak slice current, A	5.2	5.3	5.2
Horizontal beam emittance, mm mrad	0.34	0.372	0.37
Vertical beam emittance, mm mrad	0.341	0.372	0.38
Gradient of High1.Q1, T/m	-3.924	-3.38	-3.347
Gradient of High1.Q2, T/m	4.83	4.409	3.347
Gradient of High1.Q3, T/m	-4.77	-5.548	-5.355
Gradient of High1.Q4, T/m	6.861	4.813	3.683
Beam density, 10^13 cm^-3	2.8	1.9	1.3

Beam density:

$$n_b[cm^{-3}] = N_b / (\pi \sigma_{xy}^2 L_b)$$

$N_b \rightarrow$ Number of e- inside bunch

$L_b \rightarrow$ Bunch length (in FWHM)

$$\sigma_{xy} = \sqrt{\sigma_x \cdot \sigma_y}$$

DESY

Summary

- The electron beam was transversely focused to have the rms size below or equal than 50 um at the entrance / middle of plasma cell. The machine parameters were the following:
  - Laser rms spot size on the cathode: 0.3mm
  - Laser temporal profile: flat-top with 22ps FWHM length and 2ps rise and fall times
  - Gun launching phase: 0 deg w.r.t. MMMG phase
  - Gun accelerating gradient: 61 MV/m (6.73 MeV/c at on-crest phase)
  - Booster accelerating gradient: 17.5 MV/m (22 MeV/c after booster at gun and booster on-crest phases)
  - Booster phase: 0 deg w.r.t. MMMG phase
  - Main solenoid current: 365 A (corresponding to smallest beam spot on EMSY1)
  - Middle positions of H1.Q1, H1.Q2, H1.Q3 and H1.Q4: 5.19 m, 5.29 m, 5.9 m and 6.0 m correspondingly
  - Gradients of H1.Q1, H1.Q2, H1.Q3 and H1.Q4: -3.38 T/m, 4.409 T/m, -5.548 T/m and 4.813 T/m correspondingly
- The values of e-beam parameters for the case of 22 MeV/c final beam momentum will be given to Alberto for further PIC simulations

Thank you for attention !!