Self-modulation studies: Electron beam longitudinal phase space after beam-plasma interaction

- Matching of 22 MeV electron beam for beam-plasma interaction
- Further beam transport after plasma until HEDA2

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PITZ beamline for self-modulation studies

← Direction of e-beam propagation
**Goal and parameters for ASTRA simulations**

**Requirements for 100pC electron beam:**

- Smooth beam transverse focusing at the entrance / middle of plasma cell \((z = 6.25 \text{ m})\)
- Transverse beam rms size while entering plasma \(\sigma_{xy} = \sqrt{\sigma_x \cdot \sigma_y} \leq 50 \mu m\)
- Beam output after plasma (simulations by Alberto) \(\rightarrow\) input for further beam transport up to HEDA2
- Vertical beam size through TDS \((\sim 11 \text{ m})\) \(\rightarrow\) as small as possible induced energy spread by TDS
- Horizontal phase space while entering Disp3.Dipole1 \((\sim 17.2 \text{ m})\) \(\rightarrow\) best momentum resolution
- Vertical beam size at Disp3.Scr1 \((\sim 18.6 \text{ m})\) \(\rightarrow\) best temporal resolution

**Setup for beam simulations**

- Laser: Longitudinally flat-top \(\rightarrow\) 2/22\%/2 ps. Transverse rms spot size on the cathode \(\rightarrow\) 0.3 mm
- 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
- Booster starting position: \(Z=2.67 \text{ m}\)
- Solenoid scan for e-beam focus on EMSY1 \((Z=5.34 \text{ m})\)
- Many quadrupoles for further beam transport until HEDA2
- 100pC charge (200kp in ASTRA)
4 quadrupoles were used for beam transverse focusing through the plasma cell:

- High1.Q1 → position 4.79 m, focusing gradient: g(T/m)=0.3674
- High1.Q2 → position 5.15 m (5 m), focusing gradient: g(T/m)=-2.204
- High1.Q3 → position 5.55 m (5.6 m), focusing gradient: g(T/m)=4.188
- High1.Q4 → position 5.75 m (5.85 m), focusing gradient: g(T/m)=-3.27

4 quadrupoles were used for catching the beam after the plasma and going through the TDS:

- High1.Q5 → position 6.6 m (6.65 m), focusing gradient: g(T/m)=4.033
- High1.Q6 → position 6.9 m, focusing gradient: g(T/m)=-3.667 (6.9m)
- High1.Q7 → position 8.15 m (8.18 m), focusing gradient: g(T/m)=2.567
- High1.Q8 → position 8.5 m (8.655 m), focusing gradient: g(T/m)=-2.053

3 quadrupoles were used for further beam transport from TDS up to HEDA2:

- PST.QM1 → position 12.088 m, focusing gradient: g(T/m)=-1.833
- PST.QM2 → position 12.468 m, focusing gradient: g(T/m)=1.833
- PST.QT5 → position 14.748 m, focusing gradient: g(T/m)=-0.8067
Beam transverse focusing through the plasma cell

Transverse beam rms size, mm

Horizontal beam size
Vertical beam size

Zoomed part before plasma cell

Transverse emittance, mm mrad

Horizontal emittance
Vertical emittance

Zoomed part before plasma cell
Vacuum-plasma-vacuum transition studies

- Study of beam transverse focusing with additional beam divergence due to electron scattering on the window material → 0.2 mrad and 0.4 mrad were artificially added into the beam distribution.

- FLUKA simulations indicate that ~0.05 mrad induced divergence should be possible.

Transverse emittance and beam size along the beamline.

Induced beam divergence as function of thickness of window.
Setup of self-modulation experiment

Setup for self-modulation studies

Expected phase space

In front of plasma cell

After plasma cell (assuming zero initial energy spread)

In front of dipole
Resolution issues

Momentum resolution

Current case $\Rightarrow \delta p_0 = x' \frac{R_{12}}{D} \approx 3.8 \cdot 10^{-3} \Rightarrow \Delta p = \delta p_0 \cdot p_0 \approx 84 keV/c$

Best case $\Rightarrow \Delta p = \delta p_0 \cdot p_0 \approx 1 keV/c$

Temporal resolution

Current case $\Rightarrow \delta z = \frac{\varepsilon_y}{\sigma_y \cdot \sin(\varphi_y)} \cdot \frac{p_0 c}{e V_0 k} \Rightarrow \delta z \approx 0.2 mm$

TDS induced momentum spread $\Rightarrow \delta p = \frac{e V_0 k}{p_0 c} \sigma_y \Rightarrow \Delta p \approx 37 keV/c$
Electron beam was transported starting from cathode, through the TDS until HEDA2:

Much better results were obtained compared to the previously done simulations!

Expected temporal resolution for the current case $\rightarrow \sim 0.2 \text{ mm}$

Expected momentum resolution for the current case $\rightarrow \sim 84 \text{ keV/c (HEDA2)} + 37 \text{ keV/c (TDS)}$

Expected momentum resolution for the best case $\rightarrow \sim 1 \text{ keV/c (HEDA2)} + 8 \text{ keV/c (TDS)}$

Slight readjustment of quadrupole currents still needed to get the e-beam waist at $Z=6.25 \text{ m}$

Preliminary studies show that e-beam still can be well focused if the beam divergence induced due to plasma-to-vacuum transitions is less or equal to $0.2 \text{ mrad}$

E-beam transport after plasma to HEDA2 can still be improved in terms of momentum resolution (temporal resolution not very critical)

Issues to discuss…

Could the e-beam matching (through the plasma cell) be improved such that the emittance growth is minimized?

Thank you for attention!!
Electron beam distribution in horizontal phase space when entering the first dipole in HEDA2

\[ x_1 = R_{11} x_0 + R_{12} x'_0 + R_{16} \delta p_0 \]

- \( R_{11} = -0.516 \)
- \( R_{12} = 0.867 \)
- \( R_{16} = 0.905 \)

\[ |R_{11} x_0 + R_{12} x'_0| < R_{16} \delta p_0 \]

\[ x' = x \frac{R_{11}}{R_{12}} = 0.595 x \]

Current case \( \Rightarrow x' \approx 4 \cdot 10^{-3} \Rightarrow \delta p_0 = x' \frac{R_{12}}{R_{16}} \approx 3.8 \cdot 10^{-3} \Rightarrow \Delta p = \delta p_0 \cdot p_0 \approx 84 \text{keV}/c \)

Best case \( \Rightarrow x' \approx 0.2 \cdot 10^{-3} \Rightarrow \Delta p = \delta p_0 \cdot p_0 \approx 4 \text{keV}/c \)