High transformer ratio resonant PWFA working point design for EuPRAXIA@SPARC_LAB

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Summary
We designed and numerically tested an ideal working point for plasma wakefield acceleration beam drivers in external injection in the context of the EuPRAXIA project. By means of a 2.4 m plasma module we simulated the acceleration of a 30 pC electron bunch from the injection energy of 3.2 GeV up to 5 GeV. The acceleration is performed by means of an ideal train of 4 bunches (3 drivers and 1 witness). The working point was designed and optimized to maximize the energy transfer and to preserve the witness quality.

Transformer ratio \( R_T \) and resonant schemes
In beam driven schemes the transformer ratio is a merit factor that describes the energy amount that can be transferred from driver(s) to witness and can be defined as the ratio between the maximum accelerating field acting on the driver(s) and the maximum decelerating field acting on the witness

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R_T = \left| \frac{E_{\text{max}}}{E_{\text{max}}} \right|
\]

A train of \( N \) bunches, longitudinally separated by half plasma wavelength \( \lambda_p/2 \) and with ramped increasing charges can reach a transformer ratio \( R_T = 2N \).

Driving bunches parameters
- \( \gamma = 2348 \)
- \( \theta_{m(z)} = 1 \text{ mm mrad} \)
- \( \sigma_z = 3 \text{ mm} \)
- \( Q_{\text{beam}} = 40 + 140 + 270 \text{ pC} \)

Witness evolution
The witness separation respect to the last driver has been optimized to \( \Delta z = 0.46 \lambda_p \) in order to minimize the energy spread growth.

The beam loading generated by witness dramatically decreases the accelerating gradient (3.5 \( \rightarrow 1.65 \text{ GV/m} \)) and the transformer ratio (7.5 \( \rightarrow 3.65 \)). These parameters are still sufficient to accelerate the witness up to 5 GeV in 2.4 m.

The final energy spread is \( \sigma_z = 0.4 \% \) and the transverse emittance is totally preserved.

Simulation code and plasma parameters
The simulations have been performed by means of the hybrid kinetic-fluid code Architect. The mesh grid is squared with a dimension of \( 1 \mu m \times 1 \mu m \). The simulated plasma channel consists in a \( 2.4 \text{ m} \) long plateau with a plasma density \( n_p = 2.5 \times 10^{16} \text{ cm}^{-3} \) and preceded by a \( 1 \text{ cm} \) long injection ramp.

Witness acceleration
To preserve the energy spread during the evolution, the witness is injected with a triangular current shape.

Witness bunch parameters
- \( \gamma = 2348 \)
- \( \theta_{m(z)} = 0.7 \text{ mm mrad} \)
- \( \sigma_z = 16(3.8) \text{ mm} \)
- \( Q = 30 \text{ pC} \)

List of references

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