Beam dynamics in resonant plasma wakefield acceleration
@SPARC_LAB

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on behalf of SPARC_LAB collaboration
In response to the necessity of more compact accelerating structures one of the most promising ways is the plasma wakefield acceleration beam driven

- Requirements: High accelerating field and beam quality (Energy spread, emittance)

Beam Driven Plasma Acceleration @SPARC_LAB
- 1 Driver (High Charge) + Witness
- Resonant wakefield acceleration: N Drivers (Lower Charge)+ Witness
- Plasma driven FEL
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- 1 Driver (High Charge) + Witness
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**GOAL**

- Matching conditions
  - Revision of longitudinal matching for resonant scheme
Quasi Non Linear Regime

- Low charge high density bunches
- \( \tilde{Q} = \frac{N_b k_p^3}{n_0} < 1 \)
- \( \alpha = \frac{n_b}{n_0} > 1 \)
- Linear fields+resonant plasma response

**References**


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09/15/2015

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Resonant Wakefield Acceleration

- Accelerating field increases with the number of drivers
- Different longitudinal matching for drivers following the first one

Bunch(es) are treated **kinetically**
- background plasma as a **fluid**
- systematic scan in no-time
- **1cm/1 hour!**

**Equations**

\[
d_t \mathbf{p}_{\text{particle}} = q(E + c \beta_{\text{particle}} \times \mathbf{B})
\]

\[
d_t \mathbf{x}_{\text{particle}} = \beta_{\text{particle}} c
\]

\[
\partial_t n_e = -\nabla \cdot (\beta_e c n_e)
\]

\[
\partial_t \mathbf{p}_e = -\nabla \cdot (\mathbf{p}_e \otimes \beta_e c) + q(E + c \beta_e \times \mathbf{B})
\]

\[
\partial_t \mathbf{B} = -\nabla \times \mathbf{E}
\]

\[
\partial_t \mathbf{E} = c^2 \nabla \times \mathbf{B} - q \mu_0 c^3 (n_e \beta_e + n_b \beta_b)
\]
Beam Parameters

SIMULATED BUNCH PARAMETERS

- Transverse normalized emittance $\varepsilon_r = 4 \text{ mm mrad}$
- Transverse spot size $\sigma_r = 6 \mu m$
- Energy $E \approx 110\text{MeV}$
- Energy spread $\sigma_E = 0.1\%$
- Bunch length $\sigma_z = 15 - 90\mu m$
- Charge $Q = 200pC$

MEASURED DRIVER BUNCH PARAMETERS

- $\varepsilon_r \approx 4 \text{ mm mrad}$
- $E \approx 114\text{MeV}$
- $\sigma_E \approx 0.5\%$
- $\sigma_z = 30 - 60\mu m$
- $Q \approx 200 - 210pC$
Longitudinal Matching Conditions for 1st Driver

- \( k_p \sigma_z \approx \sqrt{2} \)

- Theoretical result for **linear theory** that grants the best coupling between the beam and the plasma.

- In our case \( \sigma_z \approx 75\mu m \)

- We perform a scan keeping all the bunch characteristics constant except the bunch length in order to find optimal conditions in our quasi non linear regime with \( \approx 2cm \) accelerating length.

- As a **figure of merit** for longitudinal matching we choose the peak accelerating field inside the first bubble.

- We look for a matching that grants the highest field that keeps constant during all accelerating length.

**References**


Single Driver Peak Field vs. Accelerating Length

Pre ionized plasma
\[ n_0 = 10^{16} \text{cm}^{-3} \]
\[ \lambda_p = 330 \mu m \]
\[ Q = 200 \text{pC} \]
\[ \alpha \approx 2.5 - 14.5 \]
\[ \tilde{Q} \approx 0.8 \]

Theoretical optimal matching

Best numerical result

Mismatched cases

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Best Longitudinal Conditions with Short Accelerating Length

- Theoretical optimal matching
- Best numerical result
- Previous simulation stopped at 2cm

Graph showing the electric field $E_z$ [GV/m] as a function of the longitudinal position $z$ [cm] for different values of $\sigma_z$. The green line represents $\sigma_z = 60\,\mu m$, and the black line represents $\sigma_z = 75\,\mu m$. The best numerical result is indicated by an arrow on the green line, and the theoretical optimal matching is indicated by an arrow on the black line.

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Head Erosion Mitigation by Longitudinal Matching

- Head erosion effects lead to a lack in accelerating field.
- Longitudinal matching allows to mitigate head erosion consequences.
- Most stable fields are guaranteed for $k_p\sigma_z \approx \sqrt{2}$.


Longitudinal Matching

- The beam is best matched when the driver fills completely the first bubble

\[ k_p \sigma_z \approx \sqrt{2} \]

- With short accelerating lengths longitudinal matching conditions are more relaxed

\[ k_p \sigma_z \leq \sqrt{2} \]

\[ k_p \sigma_z \approx \sqrt{2} \]

\[ k_p \sigma_z \ll \sqrt{2} \]
Injection of Second Driver

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Longitudinal Matching Conditions for 2nd Driver

- $\sigma_z \approx 60 - 75\mu m$ -> Driver tails on witness bunch

- Lower second bubble quality

- The presence of the field caused by the first driver suggest different longitudinal matching conditions for the 2nd driver

- We perform the same scan we performed for the first driver in order to look for possible advantages using resonant scheme

- We plot the Maximum accelerating field in the second bubble vs. accelerating length

- During the scan, the 1st driver characteristics and the injection distance are kept constant
Peak Field with 2 drivers

High and constant accelerating fields with very short bunches

The second driver does not require longitudinal matching to preserve fields
Advantages of Resonant Scheme

NO TAIL ON ACCELERATING REGION
Conclusions

- Well known longitudinal matching condition are still valid for the first driver

- For multiple driver configurations the longitudinal matching for the drivers following the first one is different
  - Bunches can be even shorter allowing to avoid the presence of driver tails in witness accelerating region

- 2D+1W resonant accelerating scheme:
  - 1st driver follows the longitudinal matching condition $k_p\sigma_z \leq \sqrt{2}$
  - Short 2nd driver inside the second bubble
Longitudinal matching conditions in the first bubble

\[ \kappa_p \sigma_z \leq \sqrt{2} \]

No Longitudinal matching conditions for drivers injected within the second bubble

\[ \sigma_z = 25\mu m \]
\[ \sigma_z = 60\mu m \]