Beam dynamics in resonant plasma wakefield acceleration @SPARC_LAB

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EAAC 2015 15 September 2015

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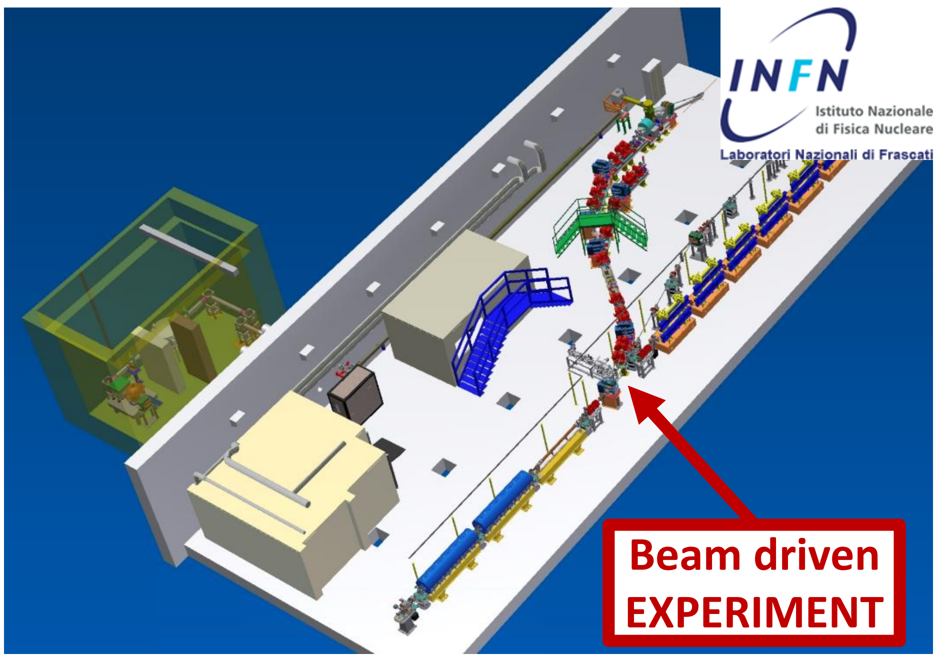
on behalf of SPARC_LAB collaboration

SPARC Layout

- 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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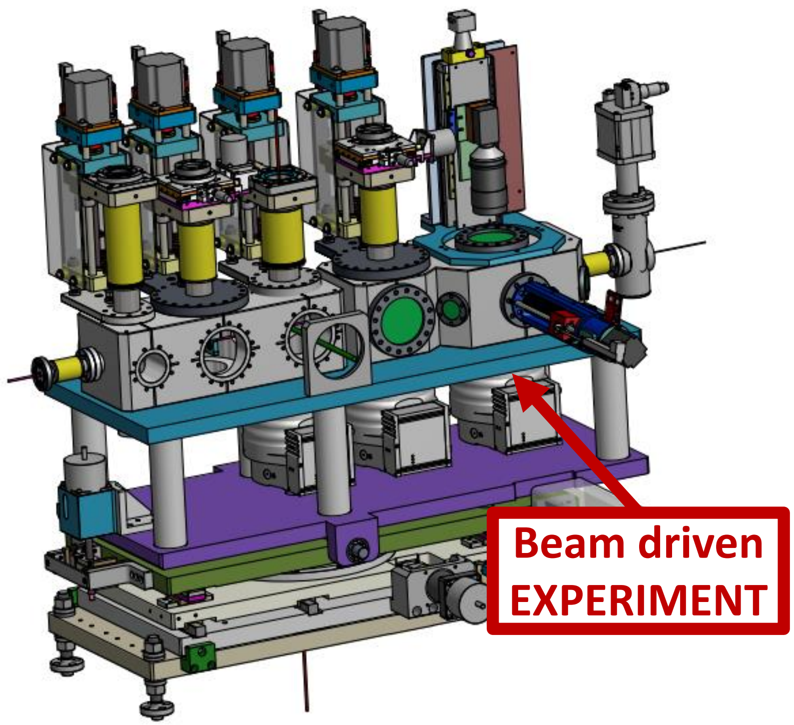

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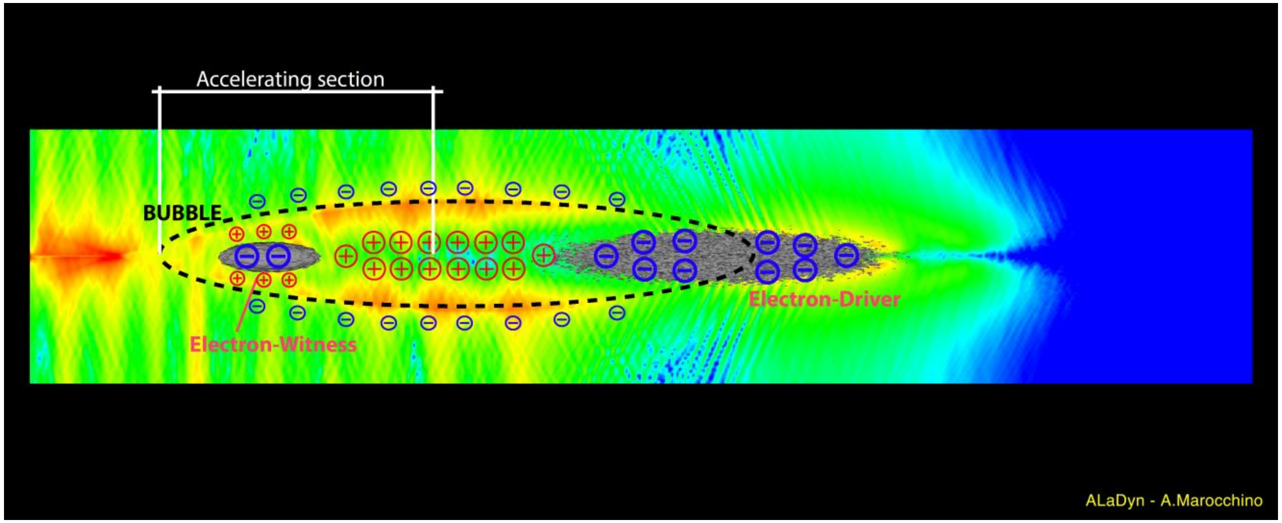
GOAL

- Matching conditions
  - Revision of longitudinal matching for resonant scheme

Quasi Non Linear Regime

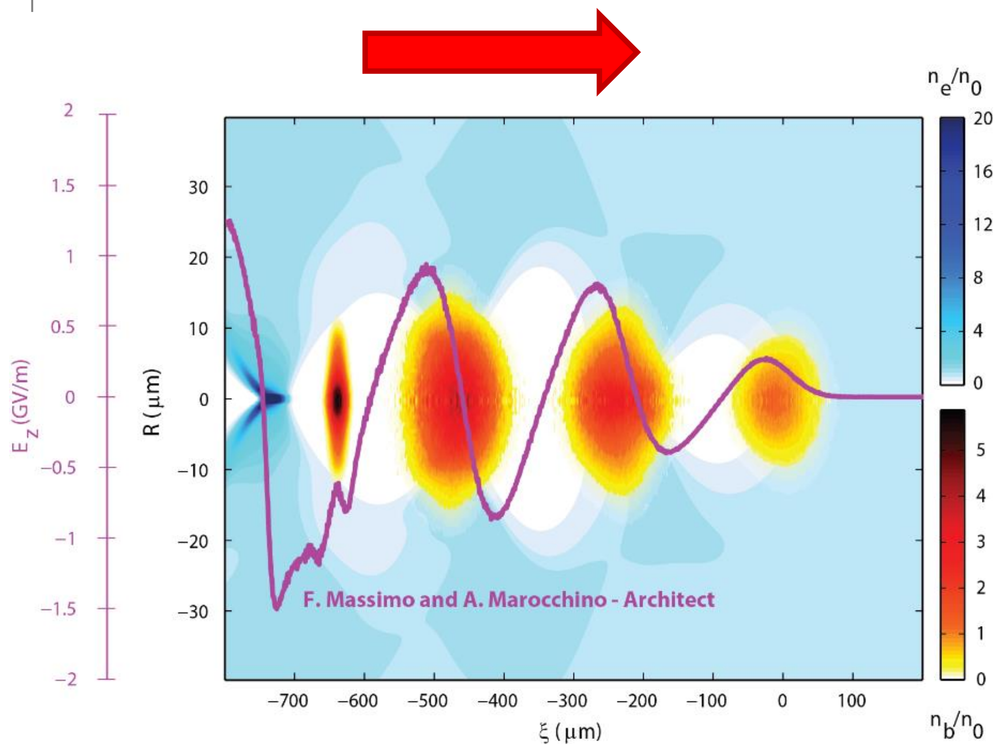


- Low charge high density bunches
- $\tilde{Q} = \frac{N_b k_p^3}{n_0} < 1$
- $\alpha = \frac{n_b}{n_0} > 1$
- Linear fields+resonant plasma response

Rosenzweig, J. B., et al. "Plasma wakefields in the quasi-nonlinear regime: Experiments at ATF." *ADVANCED ACCELERATOR CONCEPTS: 15th Advanced Accelerator Concepts Workshop*. Vol. 1507. No. 1. AIP Publishing, 2012.

Londrillo, P., C. Gatti, and M. Ferrario. "Numerical investigation of beam-driven PWFA in quasi-nonlinear regime." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 740 (2014): 236-241.

Resonant Wakefield Acceleration



- Accelerating field increases with the number of drivers

- Different longitudinal matching for drivers following the first one

Hogan, M. J., et al. "Plasma wakefield acceleration experiments at FACET." *New Journal of Physics* 12.5 (2010): 055030.

Hybrid Tool: Architect

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

Equations

$$d_t \mathbf{p}_{\text{particle}} = q(\mathbf{E} + c\boldsymbol{\beta}_{\text{particle}} \times \mathbf{B})$$

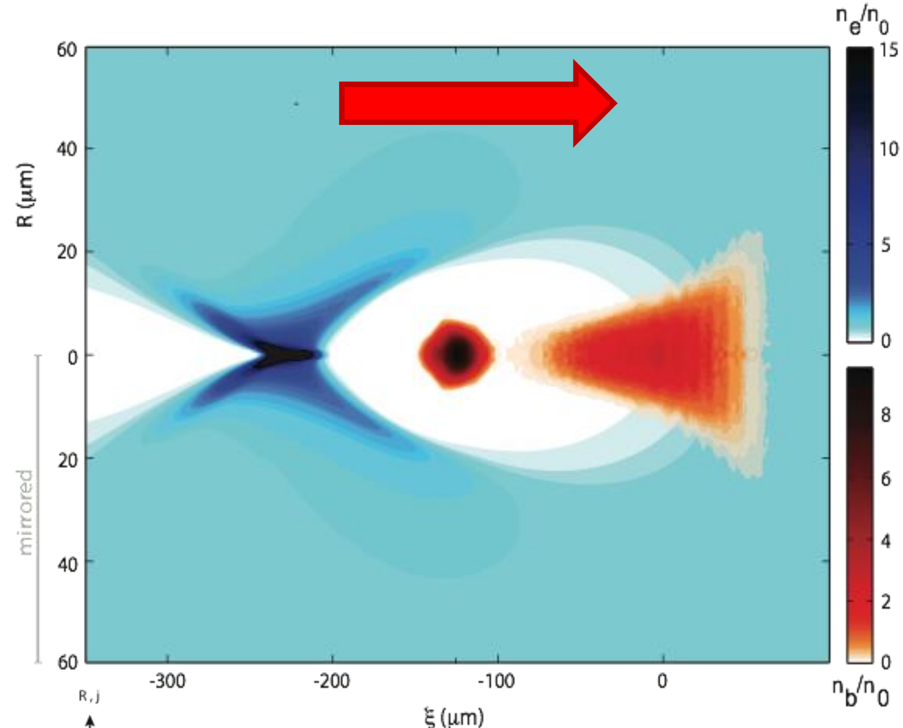
$$d_t \mathbf{x}_{\text{particle}} = \boldsymbol{\beta}_{\text{particle}} c$$

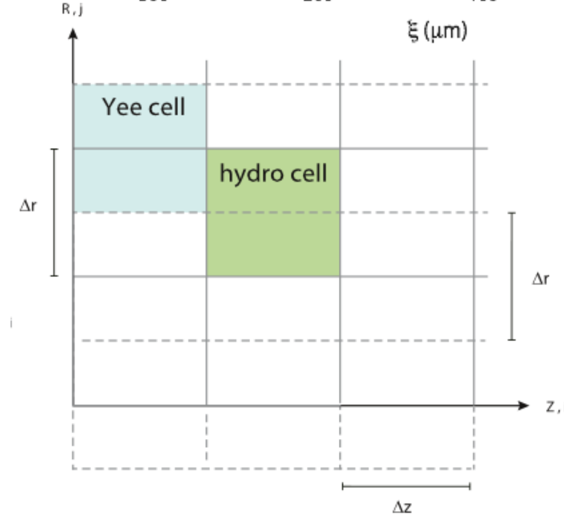
$$\partial_t n_e = -\nabla\cdot(\boldsymbol{\beta}_e c\, n_e)$$

$$\partial_t \mathbf{p}_e = -\nabla\cdot(\mathbf{p}_e \otimes \boldsymbol{\beta}_e c) + q(\mathbf{E} + c\boldsymbol{\beta}_e \times \mathbf{B})$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

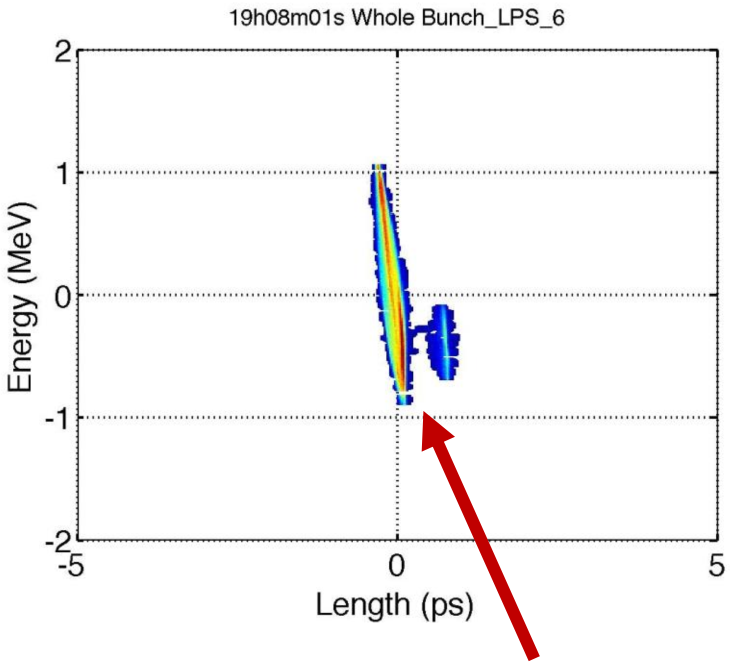
$$\partial_t \mathbf{E} = c^2 \nabla \times \mathbf{B} - q\mu_0 c^3 \left(n_e \boldsymbol{\beta}_e + n_b \boldsymbol{\beta}_b\right)$$





Beam Parameters

SIMULATED BUNCH PARAMETERS



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

MEASURED DRIVER BUNCH PARAMETERS

- $\varepsilon_r \cong 4\ mm\ mrad$
- $E \cong 114 MeV$
- $\sigma_E \cong 0.5\%$
- $\sigma_z = 30 - 60 \mu m$
- $Q \cong 200 - 210 pC$

Longitudinal Matching Conditions for 1st Driver

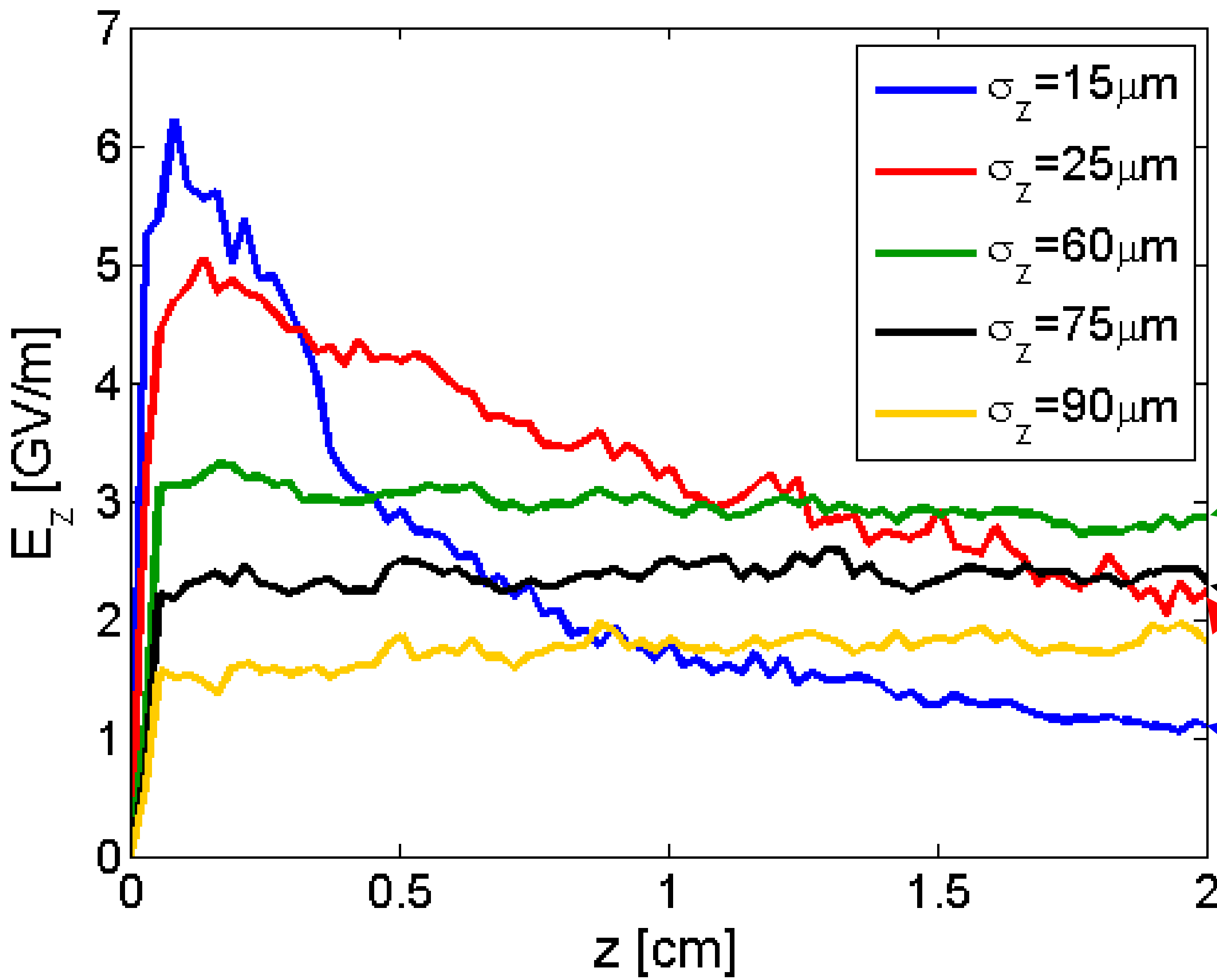
- $k_p \sigma_z \cong \sqrt{2}$

Joshi, C., et al. "High energy density plasma science with an ultrarelativistic electron beam." *Physics of Plasmas (1994-present)* 9.5 (2002): 1845-1855.
Lu, W., et al. "Limits of linear plasma wakefield theory for electron or positron beams." *Physics of Plasmas (1994-present)* 12.6 (2005): 063101.

- Theoretical result for **linear theory** that grants the best coupling between the beam and the plasma
- In our case $\sigma_z \cong 75\mu m$
- **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 $\cong 2cm$ 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

Single Driver Peak Field vs. Accelerating Length

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

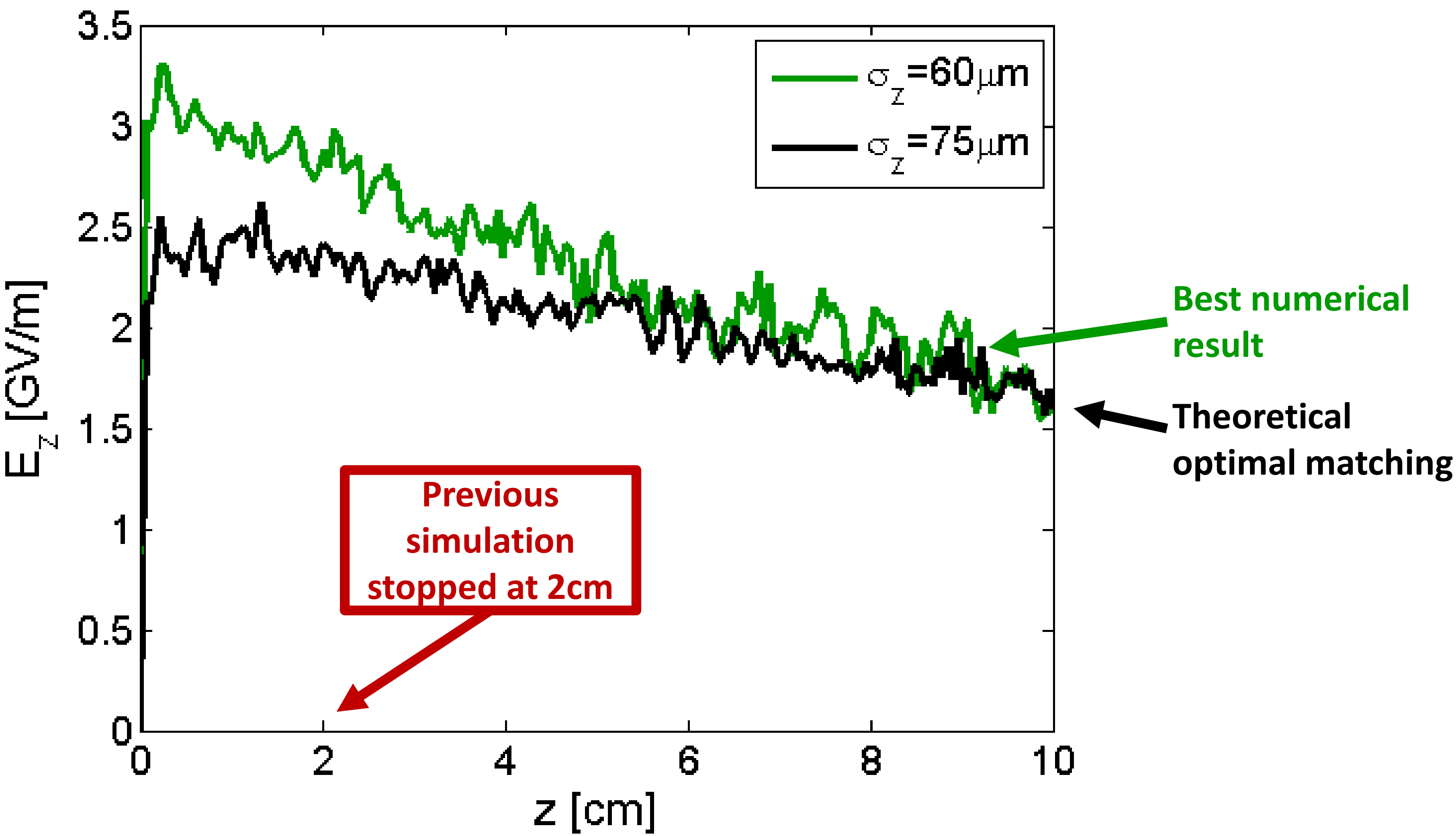


Best numerical result

Theoretical optimal matching

Mismatched cases

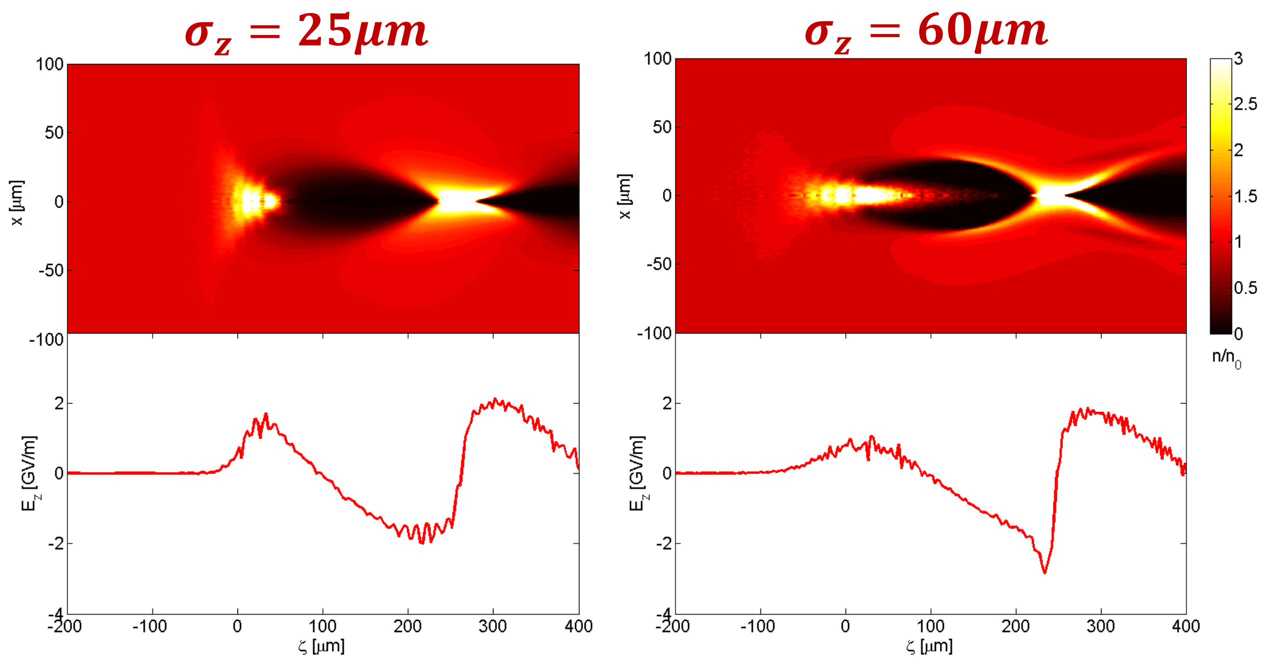
Best Longitudinal Conditions with Short Accelerating Length



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

$$k_p \sigma_z \cong \sqrt{2}$$



Blumenfeld, Ian, et al. "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator." *Nature* 445.7129 (2007): 741-744.

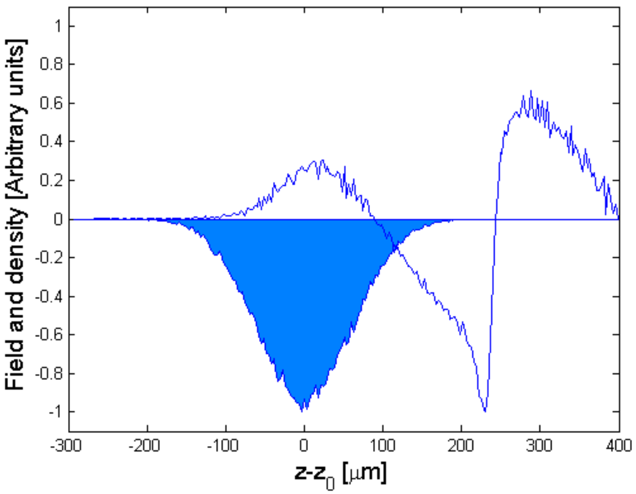
Zhou, M., et al. "Beam head erosion in self-ionized plasma wakefield accelerators." *Particle Accelerator Conference, 2007. PAC. IEEE*. IEEE, 2007.

An, W., et al. "Strategies for mitigating the ionization-induced beam head erosion problem in an electron-beam-driven plasma wakefield accelerator. "*Physical Review Special Topics-Accelerators and Beams* 16.10 (2013): 101301.

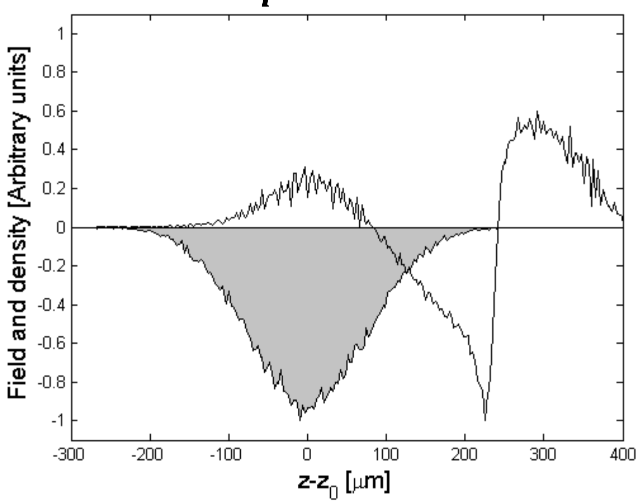
Longitudinal Matching

- The beam is best matched when the driver fills completely the first bubble
- $k_p\sigma_z \cong \sqrt{2}$
- With short accelerating lengths longitudinal matching conditions are more relaxed
- $k_p\sigma_z \leq \sqrt{2}$

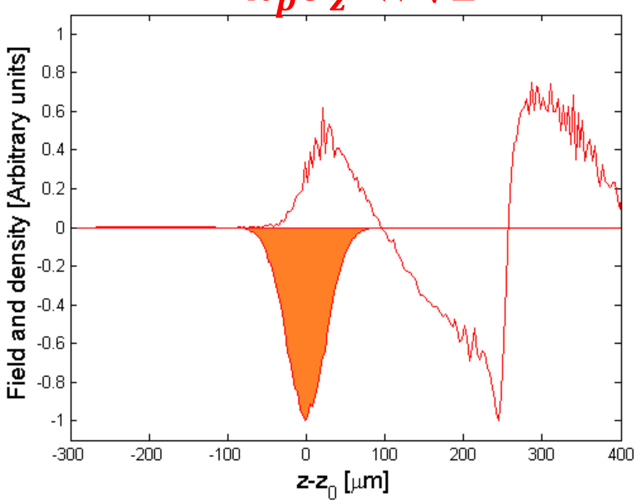
$k_p\sigma_z < \sqrt{2}$



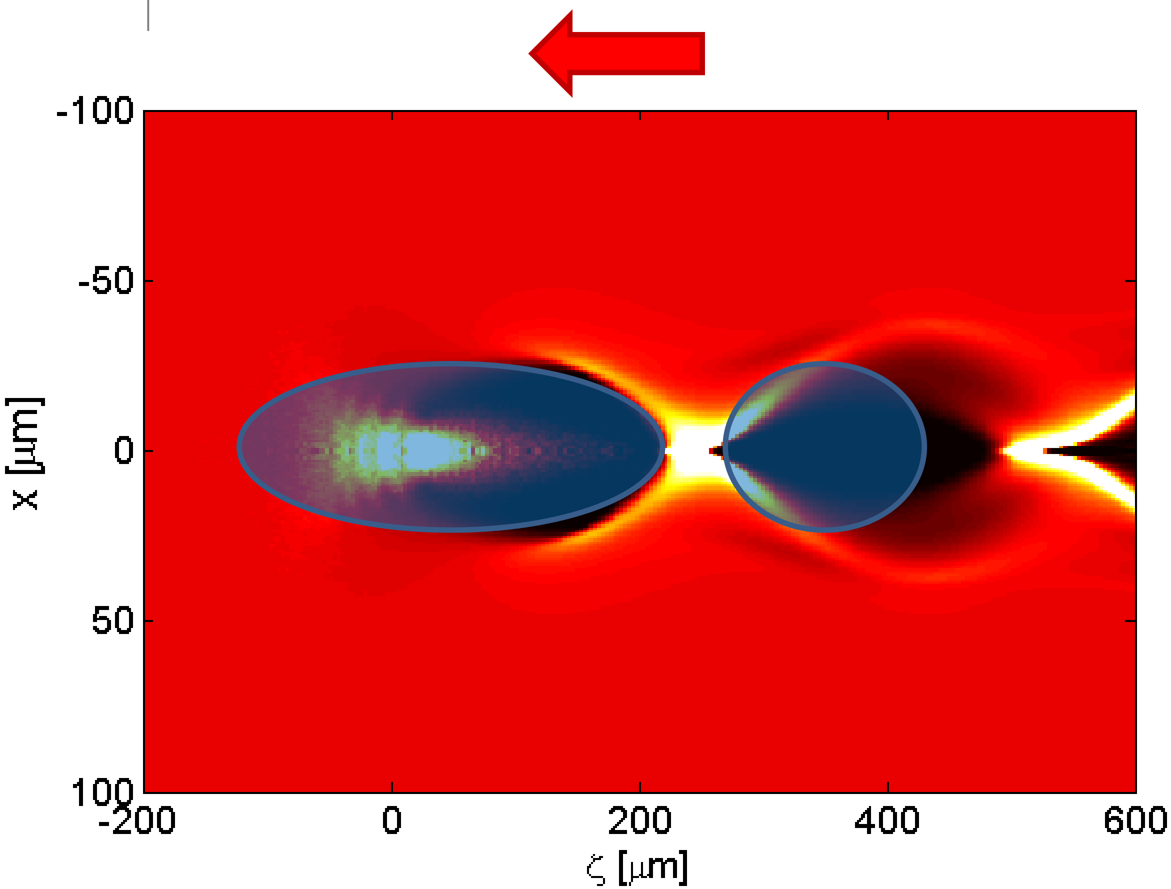
$k_p\sigma_z \cong \sqrt{2}$



$k_p\sigma_z \ll \sqrt{2}$



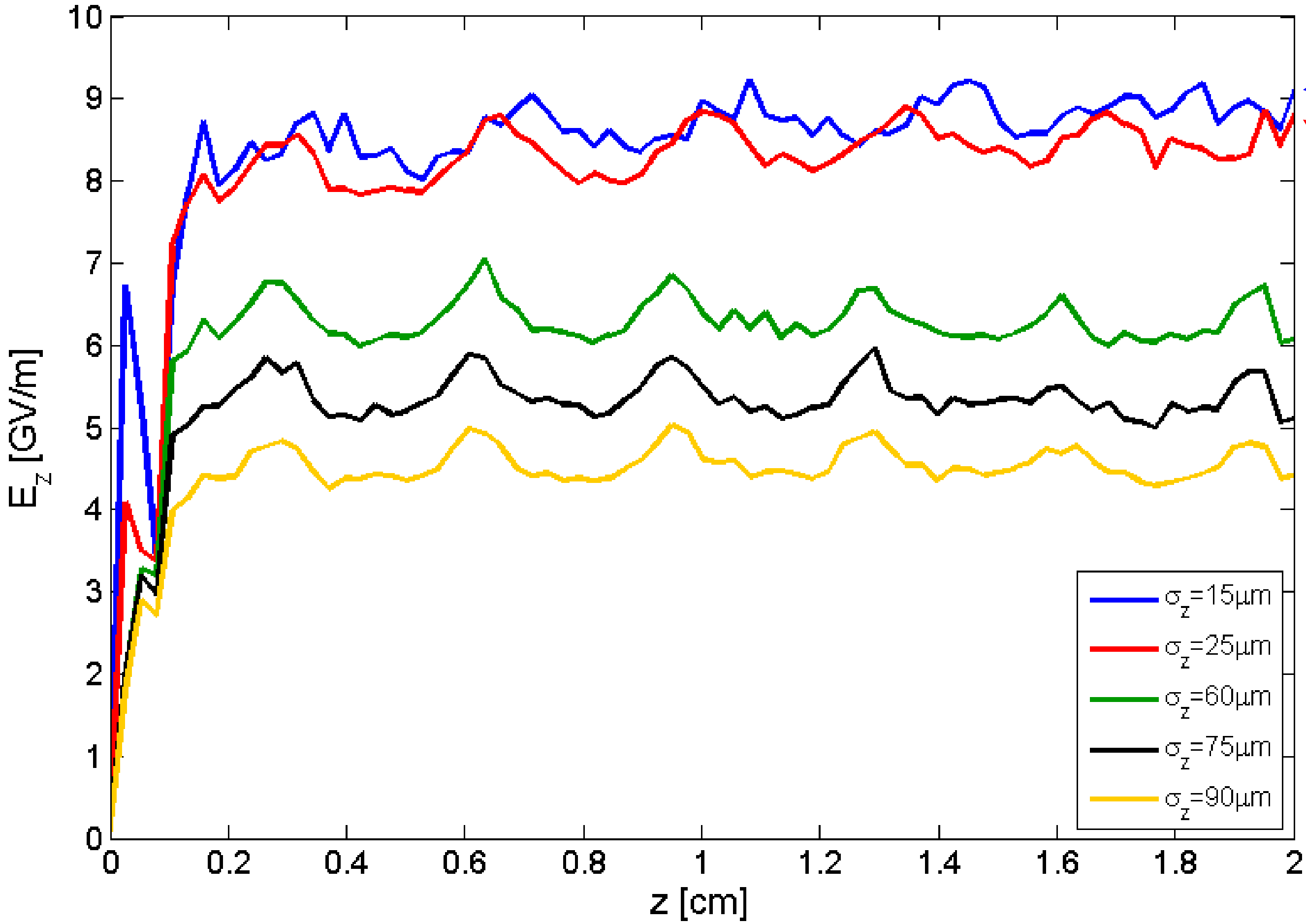
Injection of Second Driver



Longitudinal Matching Conditions for 2nd Driver

- $\sigma_z \cong 60 - 75\mu m$-> **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**

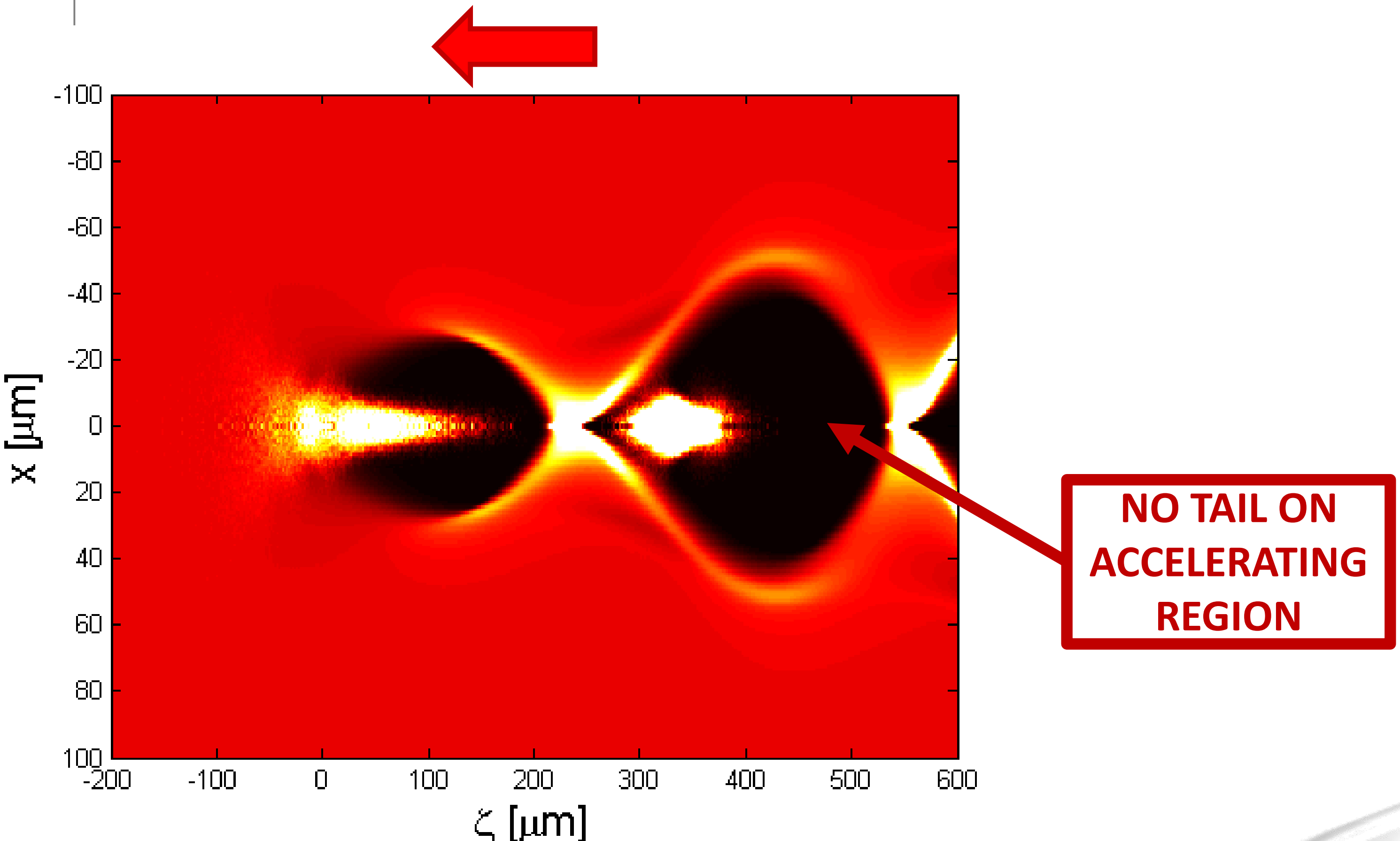
Peak Field with 2 drivers



High and constant accelerating fields with very short bunches

- The second driver does not require longitudinal matching to preserve fields

Advantages of Resonant Scheme



Conclusions

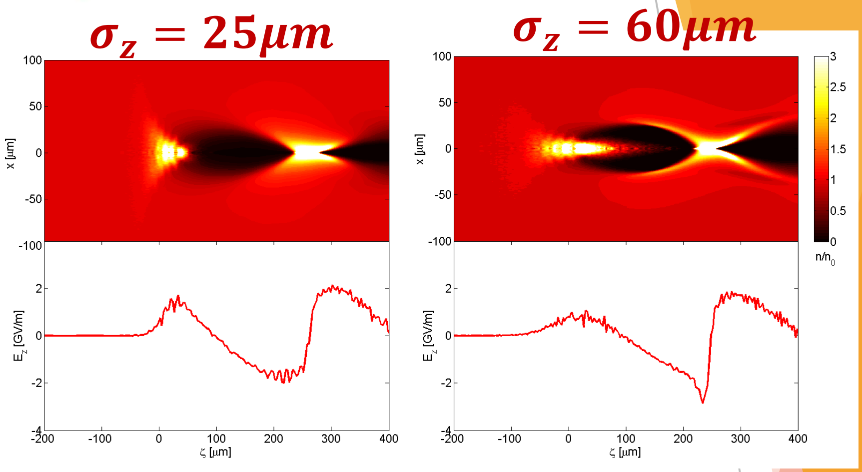
- **Well known longitudinal matching condition are still valid for the first driver**

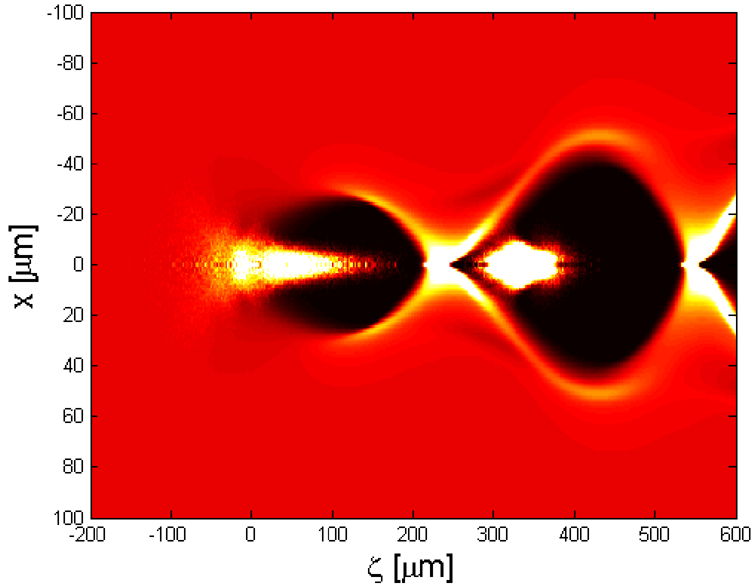
- **For multiple driver configurations the longitudinal matching for the drivers following the first one is different**
  - Bunches can be even shorter allowing to avoid the presence of driver tails in witness accelerating region

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

Longitudinal matching conditions in the first bubble

$$k_p\sigma_z \leq \sqrt{2}$$





No Longitudinal matching conditions for drivers injected within the second bubble