EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

EuPRAXIA Preparatory Phase

EuPRAXIA@SPARC_LAB Working Point optimization via PIC numerical simulations

Parise G., Cianchi A., Del Dotto A., Giannessi L., Giribono A., Griseri G., Romeo S., Rossi A.R., Sbragaglia M., Silvi G.J., Simeoni D., Tamburo S., Ferrario M.

On behalf of the EuPRAXIA@SPARC_LAB collaboration

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INFN Istituto Nazionale di Fisica Nucleare LABORATORI NAZIONALI DI FRASCATI

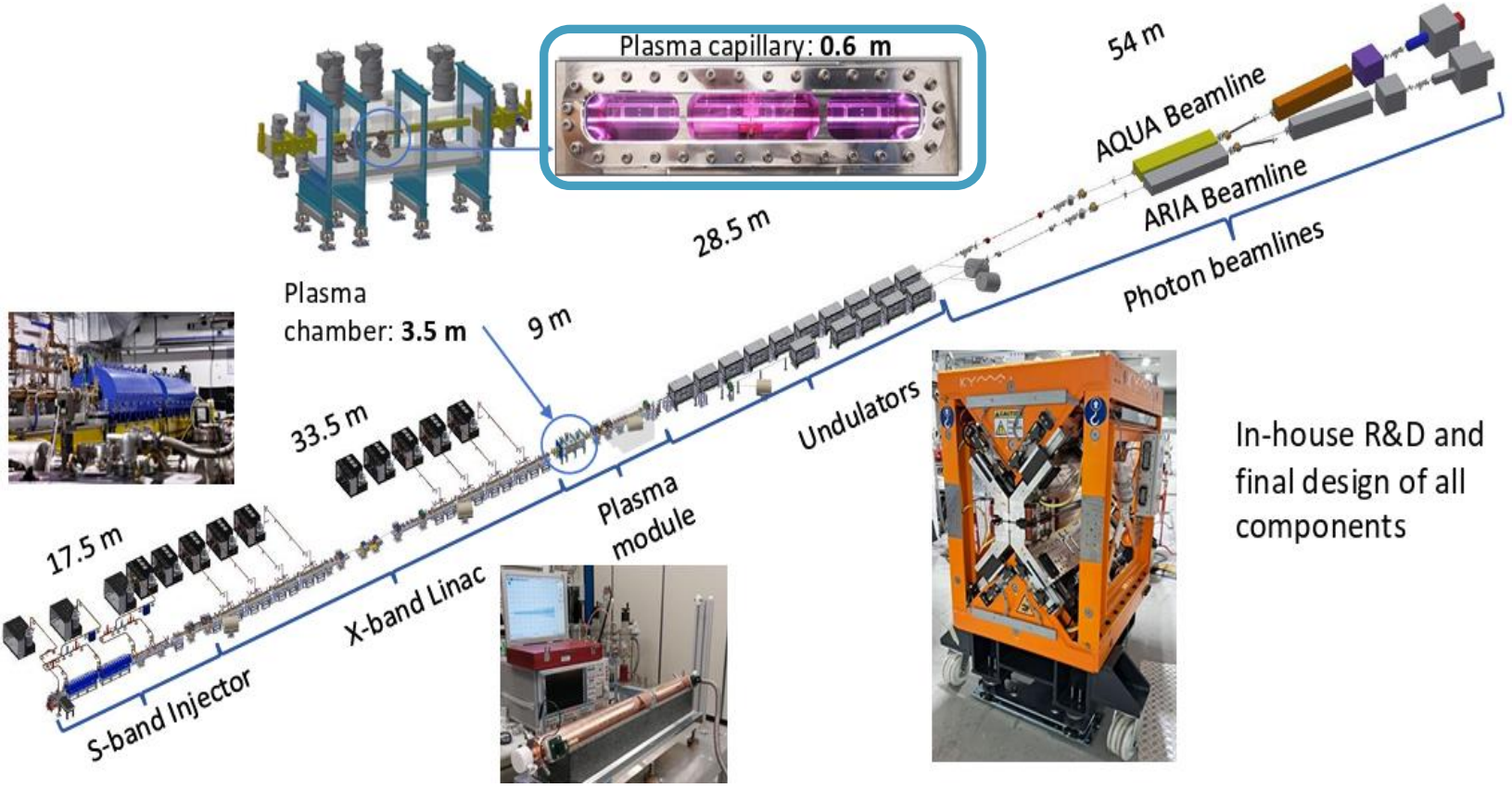
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

EuPRAXIA_PP Final meeting
EuPRAXIA_DN Conference
Portoferraio, Italy – September 21st, 2026

Funded by the European Union

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

Motivations



In-house R&D and final design of all components

	FEL quality
E [GeV]	~ 1
$\varepsilon_{x,y}$ [mm mrad]	≤ 0.6-1
$\sigma_{E,slice}/E$ [%]	≤ 0.04-0.1
I_{peak} [kA]	> 1
σ_z [μm]	< 5

- ✓ EuPRAXIA@SPARC_LAB will be the first user facility to drive a Free Electron Laser (FEL) beam accelerated from a plasma module
- ✓ Need to study the FELs beams that require high-current and high-quality
- ✓ The Technical Design Report [1] indicates a reference Working Point (WP)
- ✓ We performed accurate Particle-in-Cell simulations with the code FBPIC of the operational parameters of the WP

[1] Alesini, D., et al. Eupraxia@sparc_lab Technical Design Report, oar.it (2026) doi:10.15161/oar.it/k57qz-5qk09

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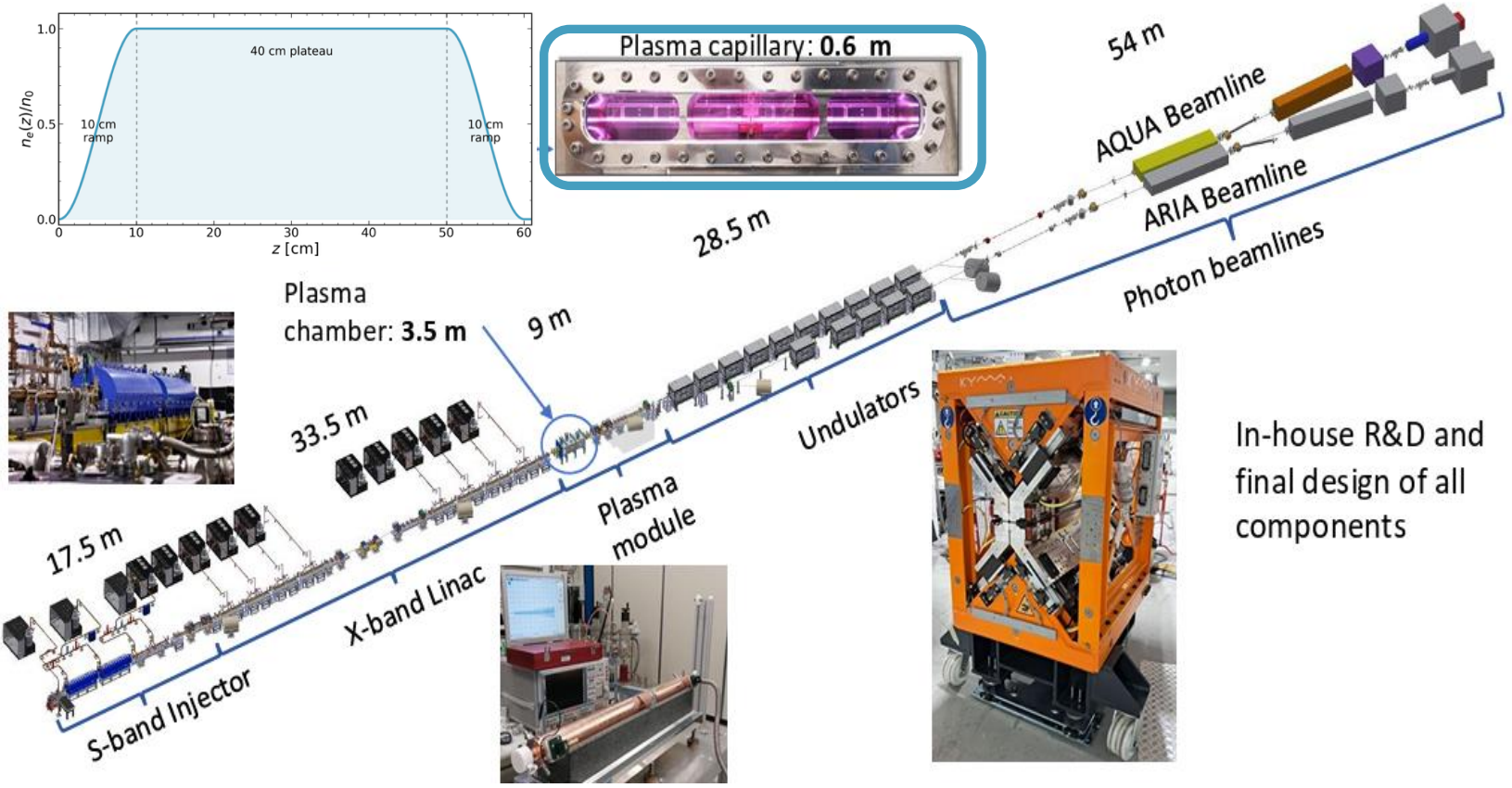

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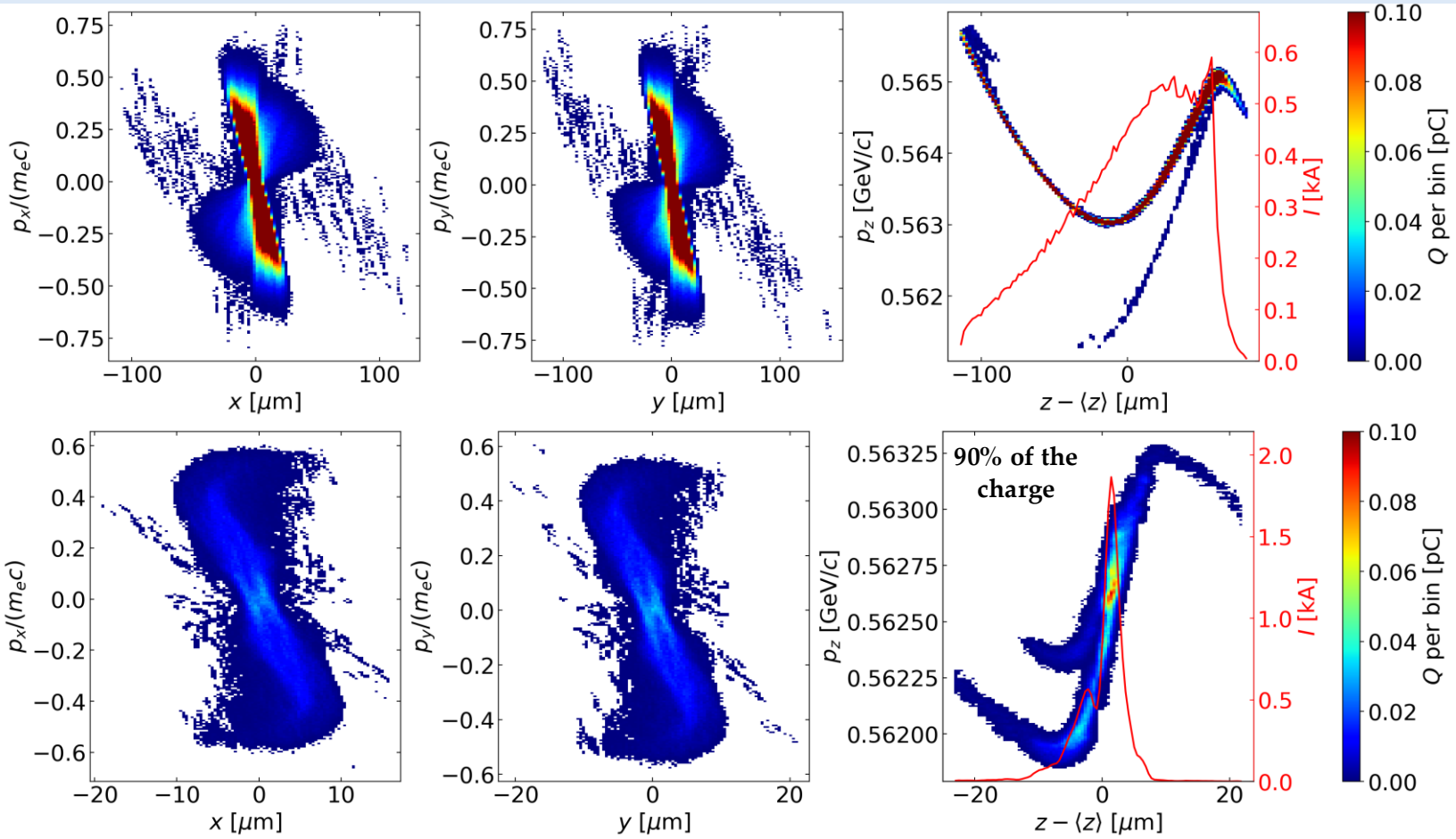
Reference WP at plasma entrance



	Driver	Witness
Q [pC]	200	30
$\sigma_{x,y,z}$ [μm]	(8.8, 9.2, 44)	(3.7,3.8,3.9)
E [MeV]	0.564	0.562
$\varepsilon_{x,y}$ [mm mrad]	(1.6,1.66)	(0.59,0.6)
$\sigma_{E,sliced}/E$ [%]	0.12	0.06
$\alpha_{x,y}$	(0.67,0.71)	(1.32,1.23)
$\beta_{x,y}$ [m]	(0.054,0.056)	(0.026,0.027)

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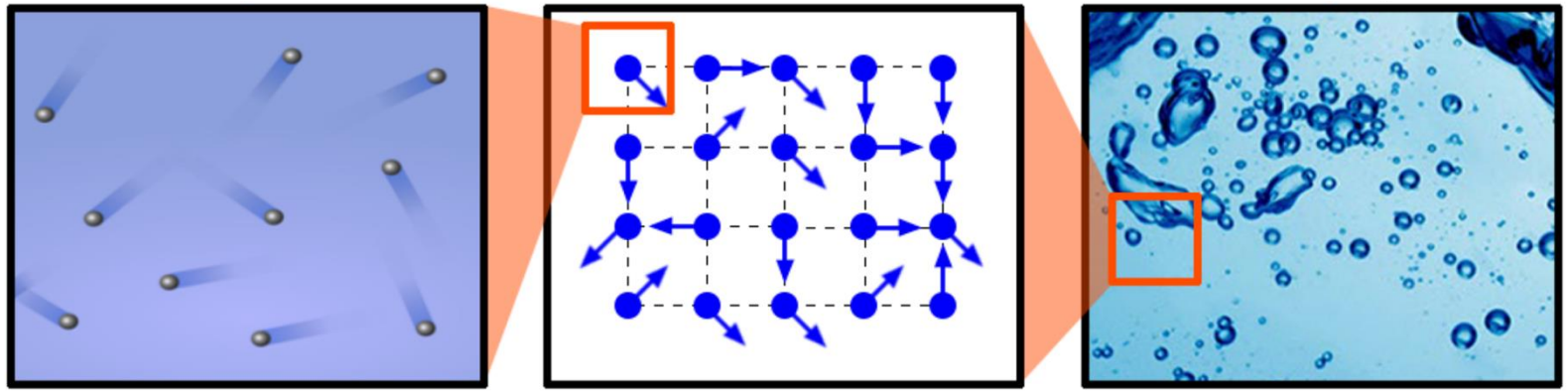
Numerical models

Funded by the European Union

Plasma Solvers

Microscopic | Kinetic | Macroscopic



Particle-In-Cell (PIC) Solvers [1]

Solutions of kinetic equations via bottom-up simulations of Lagrangian particles

$$\mathbf{F} = \frac{d\mathbf{p}}{dt}$$

Fluid Solvers [2]

Coarse grained theories that solve for the first moments of the kinetic distribution function

$$M^{(n)}(\mathbf{x},t) \propto \int f(\mathbf{x},\mathbf{p},t)\mathbf{p}^n d\mathbf{p}$$

Both model works in **cylindrical symmetry**

Maxwell Solvers

Analytical Fourier-Bessel

- ✓ Solution in Fourier Space
- ✓ Analytical integration
- ✓ Dispersion-free

Finite Difference time Domain

- ✓ Space and time discretization
- ✓ Staggered quantities for 2nd order
- ✓ Years of development

[1] Lehe, R., et al., Comp. Phys. Comm., 203, 66–82 (2016)
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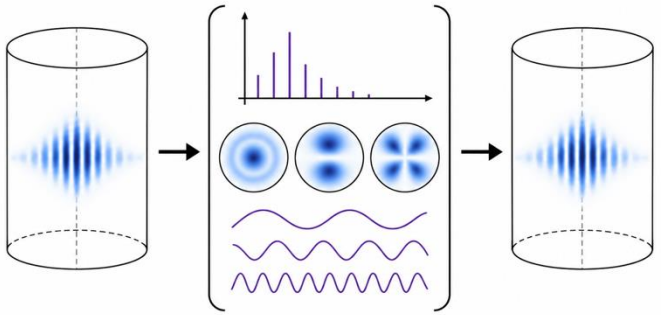

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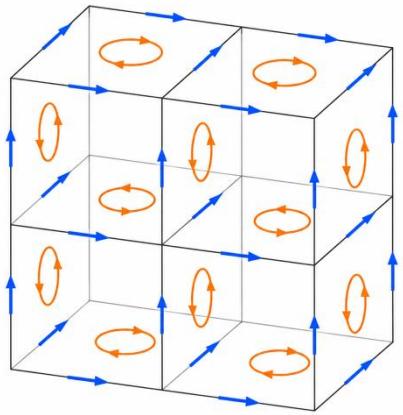

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Frozen Fields (FF) approximation

Both the algorithm can be developed to solve only the plasma fields frozing the driver and witness ones

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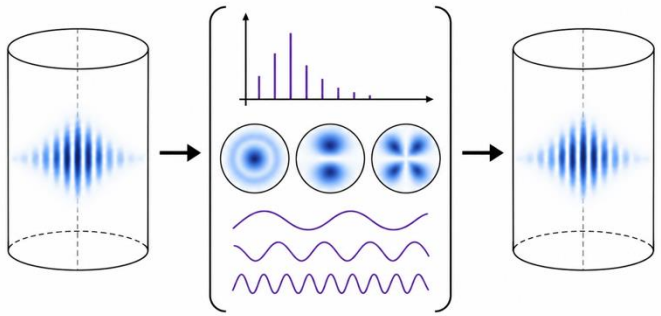

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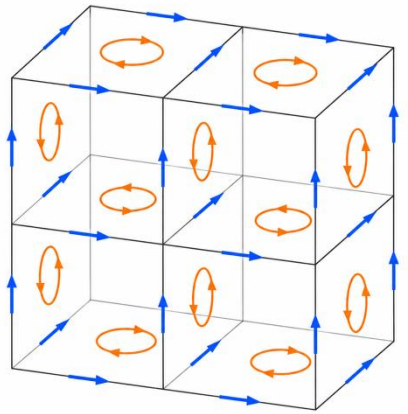

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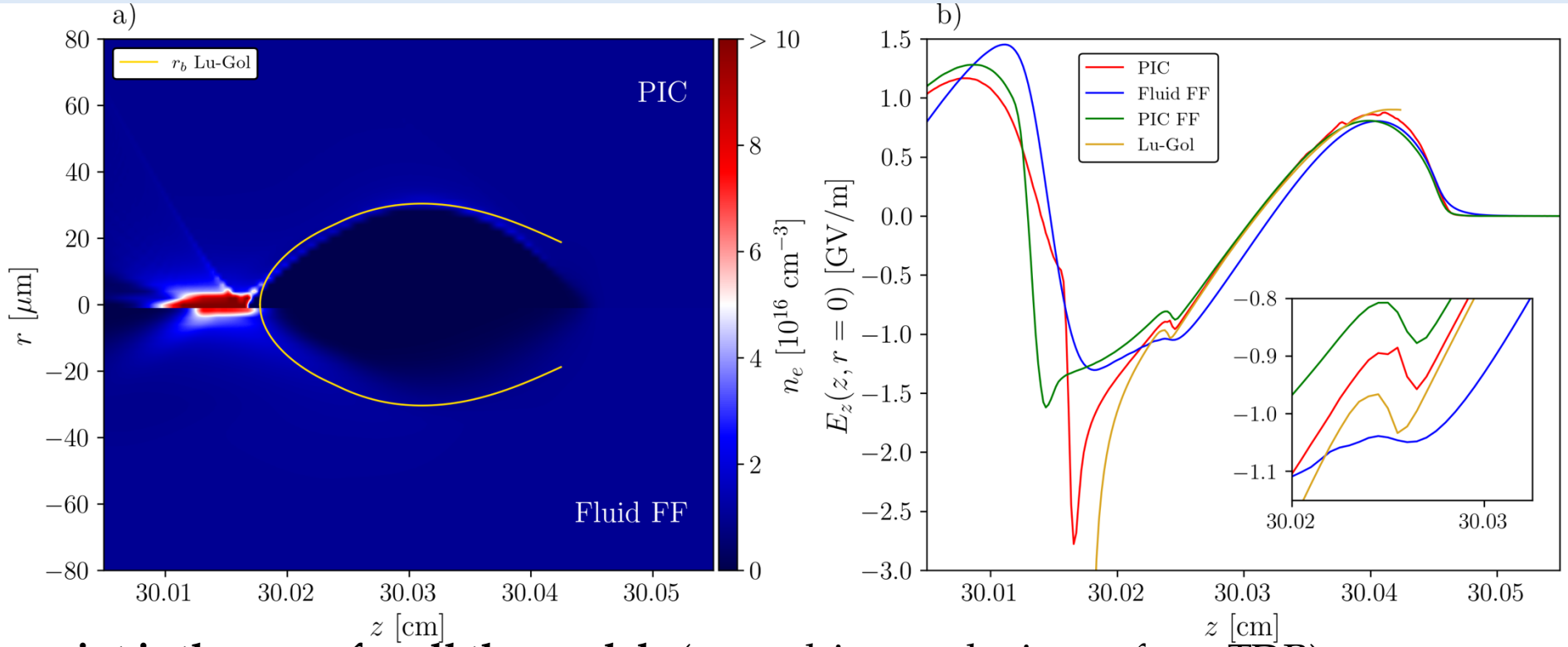
Wakefield and beam loading



- ✓ The **working point is the same for all the models** (same driver and witness from TDR)
- ✓ To have another comparison, we used a Lu-Golovanov (Lu-Gol) [1][2] analytical model to compute r_b and E_z
- ✓ The density color map shows two bubbles with different lengths and radii
- ✓ The main difference is in the **witness beam loading** (inset figure b)
  1. PIC → overloading
  2. Fluid → correct loading
- ✓ Transverce dynamic is similar → the match is correct with both models
- ✓ The overloading leads to an increase in energy spread

[1] Lu, W., et al., Phys. Rev. Lett., 96 ,16, (2006)

[2] Golovanov, A., et al., Phys. Rev. Lett. 130, 10, (2023)

Transverse dynamic and spread growth

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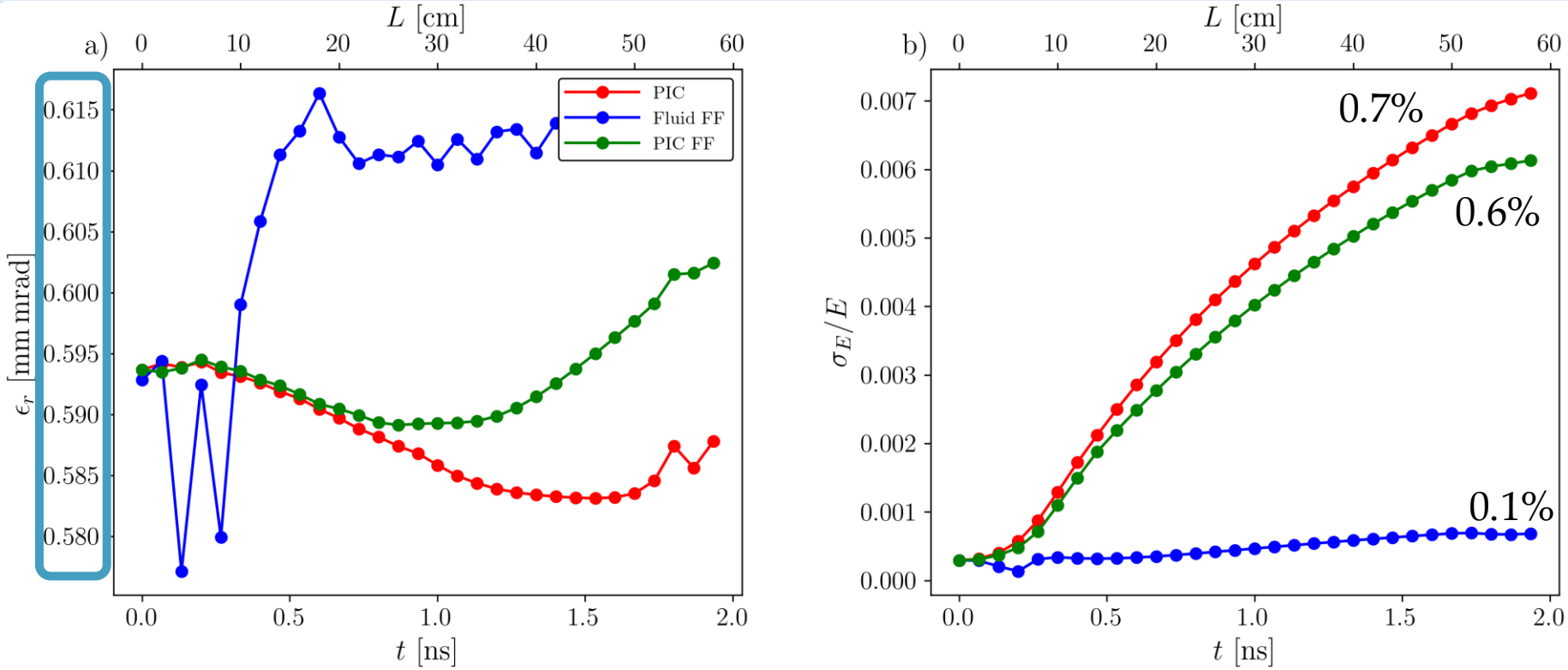

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Bubble geometry

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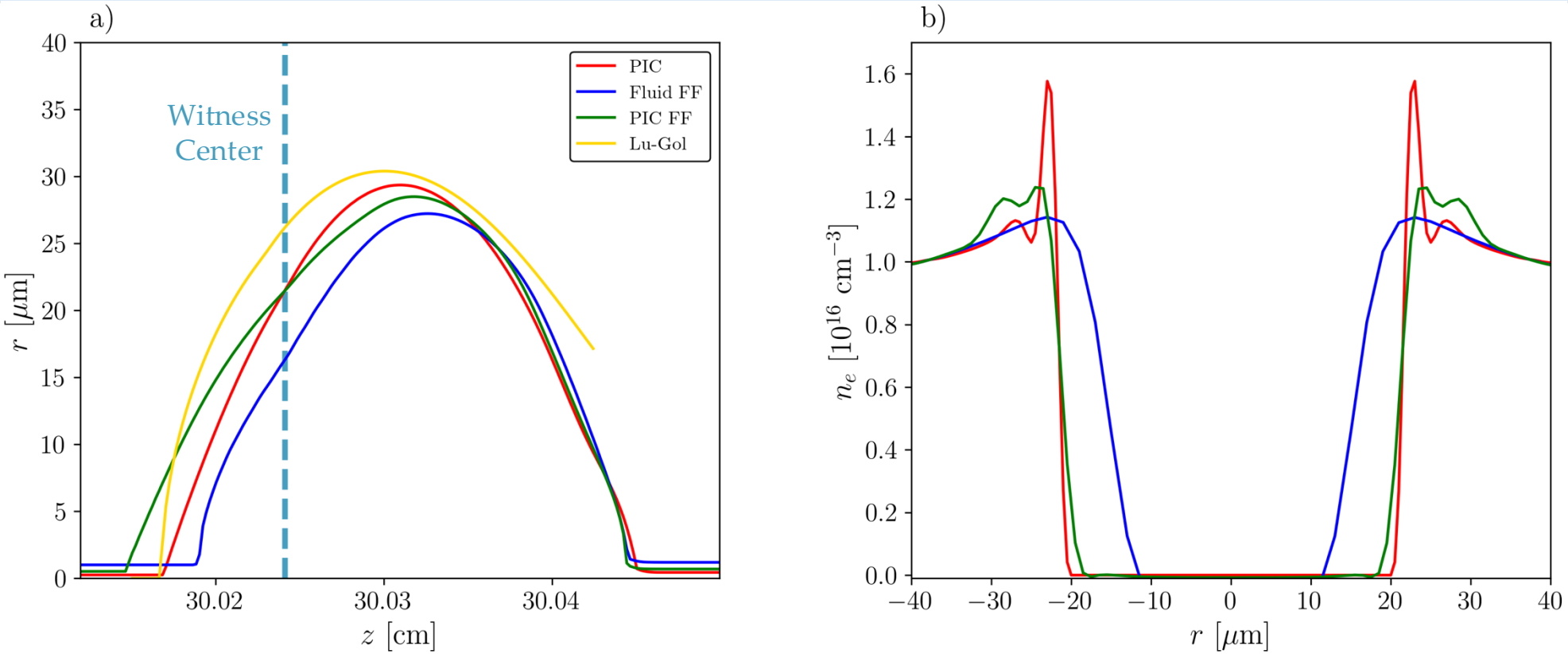
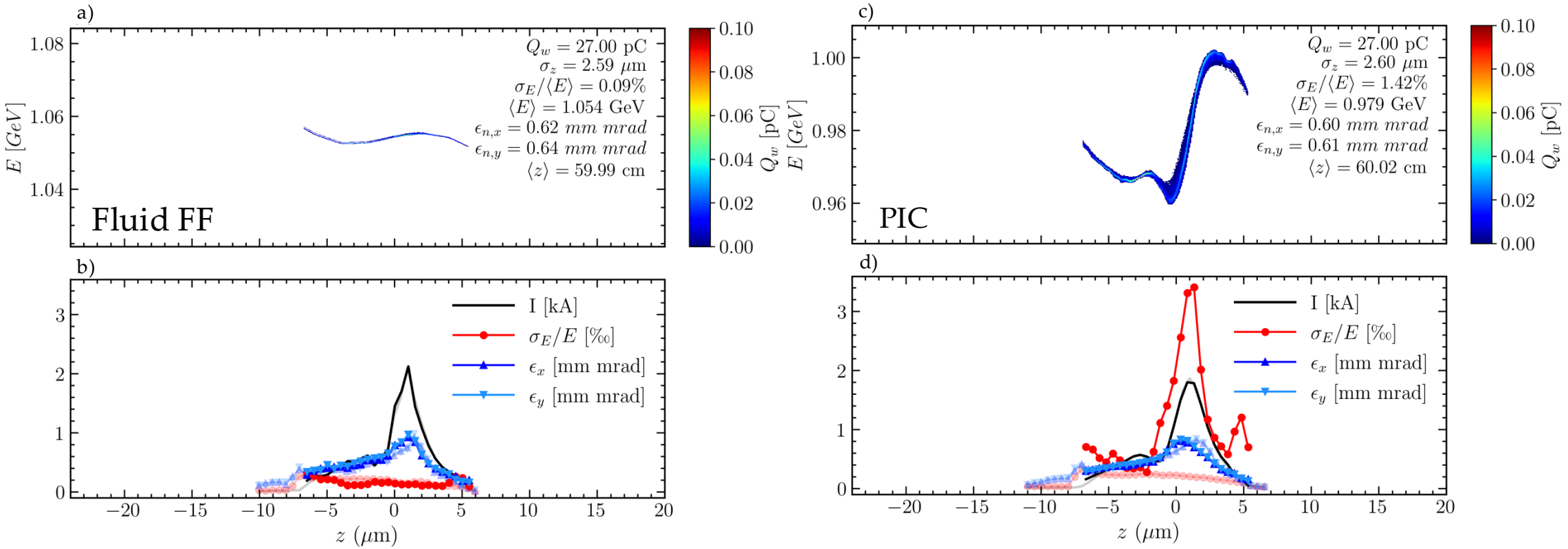


- ✓ The bubble boundary is identified as the first radial position where the plasma electron density recovers to 75% of its local unperturbed value
- ✓ Two sources of differences:
  1. The models used to solve **the plasma** and Maxwell equations
  2. Frozen Field approximation
- ✓ The different loading and energy spread growth are due to bubble geometry

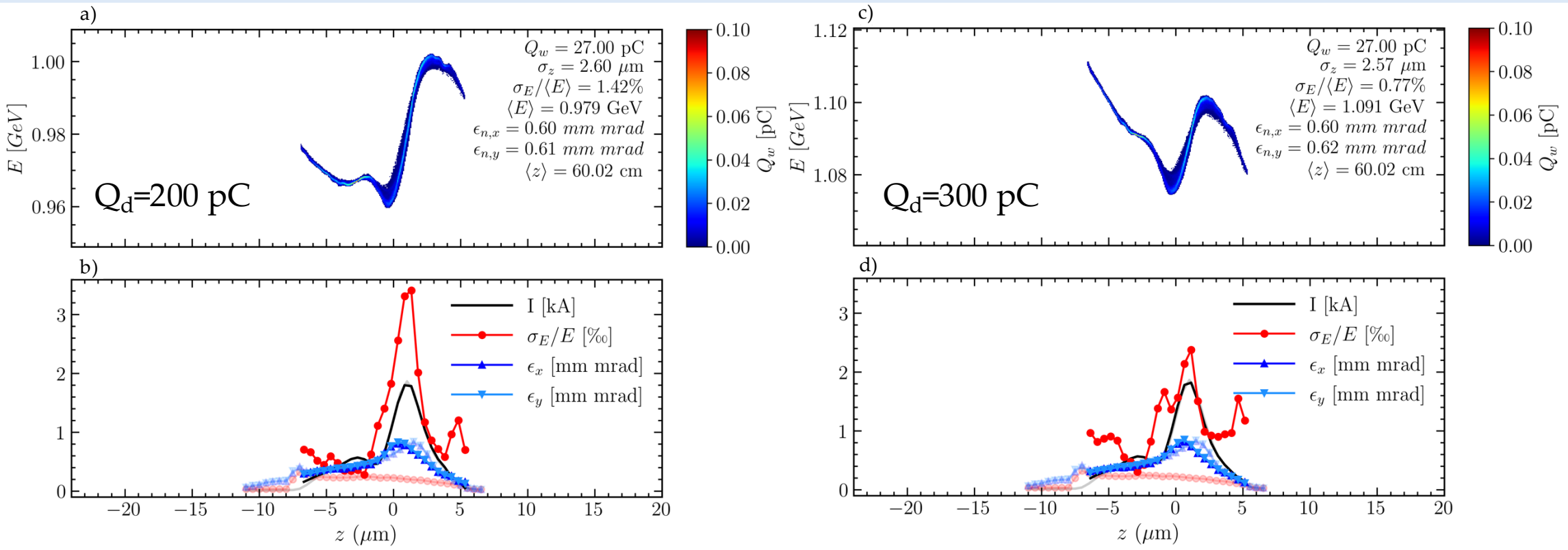
Tzoufras M., et al., Phys. Rev. Lett., 101, 145002, (2016)

Witness phase space



- ✓ Fluid FF predicts a flatter loaded field and a longitudinal phase space that fills the FEL requirements
- ✓ Self-consistent PIC shows stronger energy chirp and projected energy-spread growth because of overloading
- ✓ The high-current core has:
  1. good sliced emittance ✅
  2. projected spread and sliced outside the tolerance range ❌

PIC optimization strategy



- ✓ The reference WP is overloaded in a self-consistent PIC simulation
- ✓ We scanned four key parameters:
  1. **Driver charge Q_d**
  2. Plasma density n_0
  3. Driver and witness distance $d_{d\text{-}w}$
  4. Witness current I_w

With some constraints:

1. <500 pC (X band)
2. $0.6 < n0 < 1.5 \times 10^{16}$ [cm^{-3}] (E_z and $d_{d\text{-}w}$)
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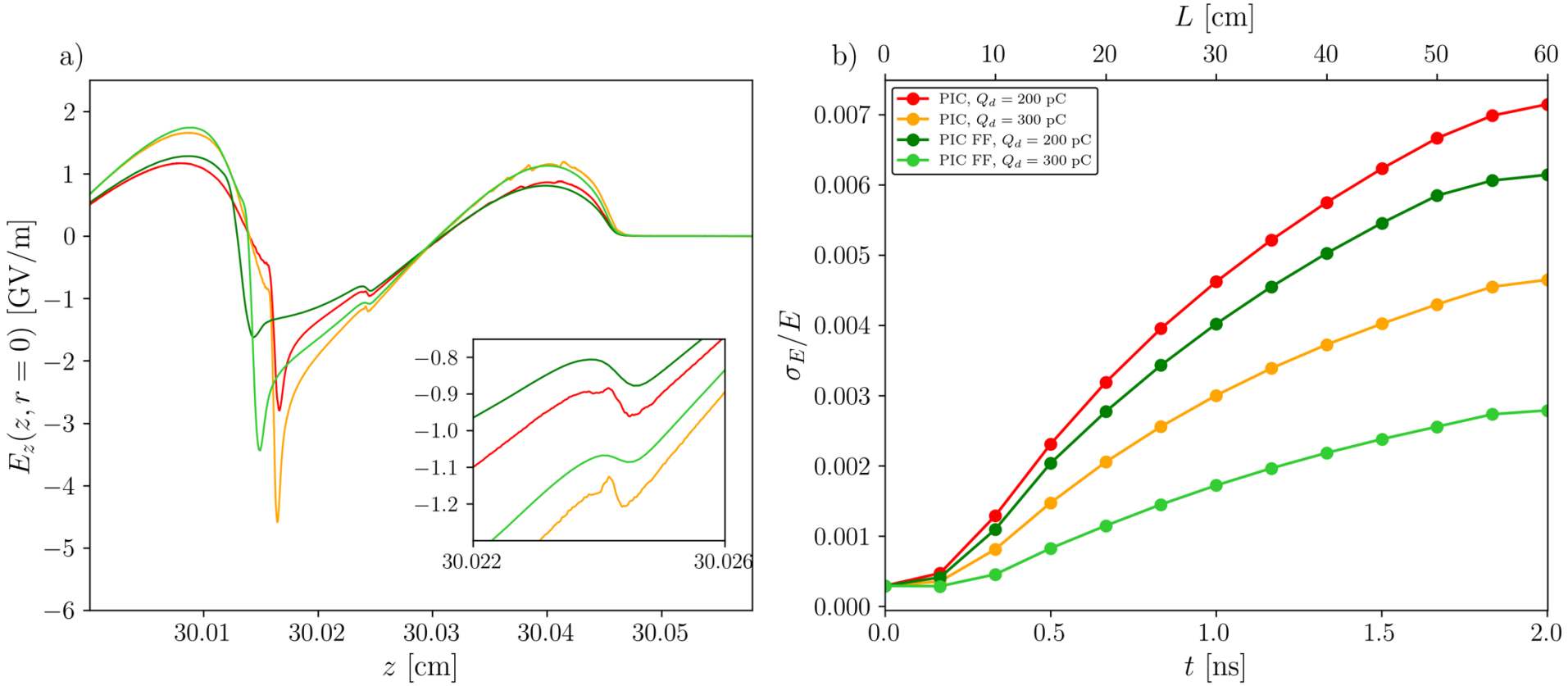

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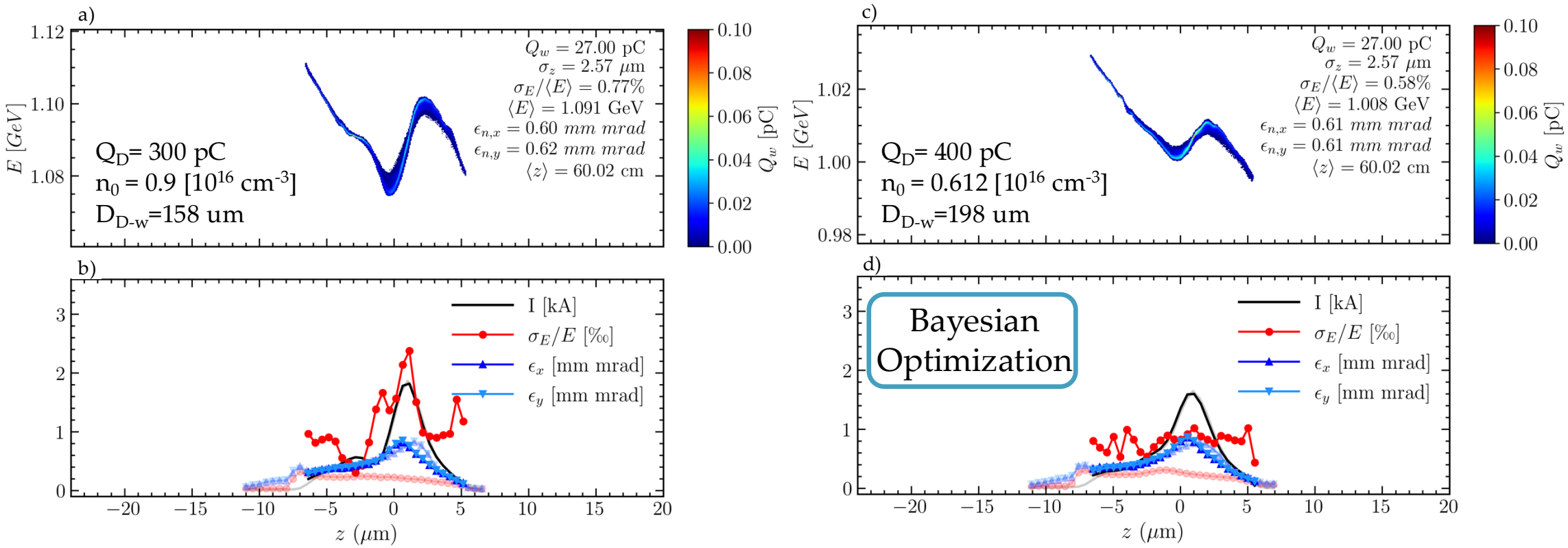

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Through the optimized WP

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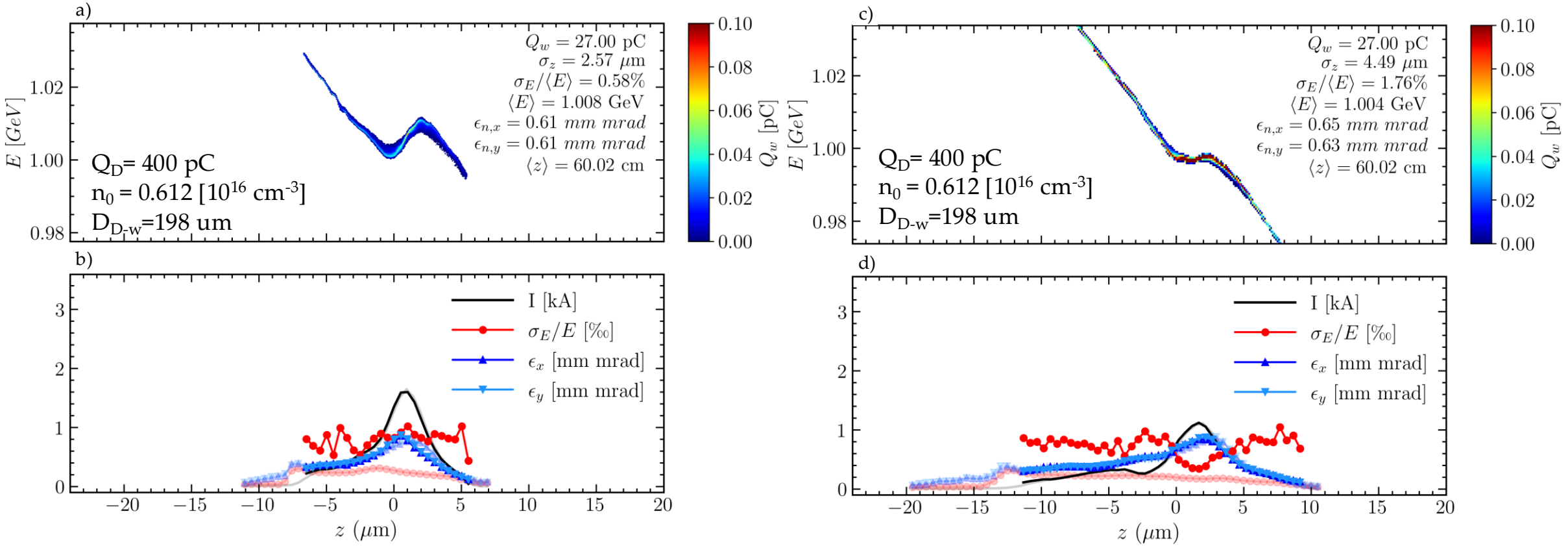

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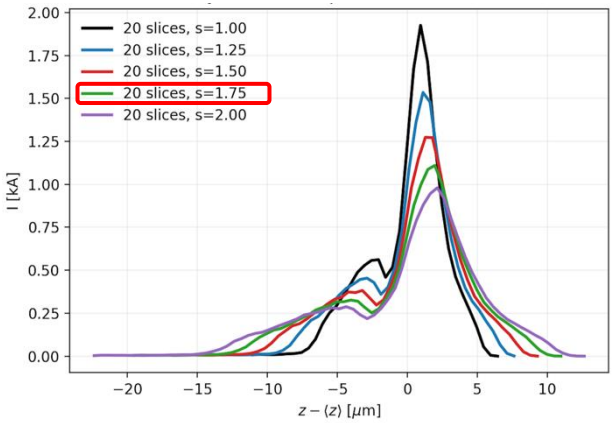

Conclusions and future perspective

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Conclusions:

- ✓ The **TDR working point** was reassessed with self-consistent PIC simulations
- ✓ PIC and Fluid models predict similar transverse dynamics but **different beam loading**
- ✓ The difference is traced back to the plasma-bubble geometry and sheath structure
- ✓ A new PIC-optimized working point reduces the projected energy spread while **preserving FEL-quality** core parameters by changing:

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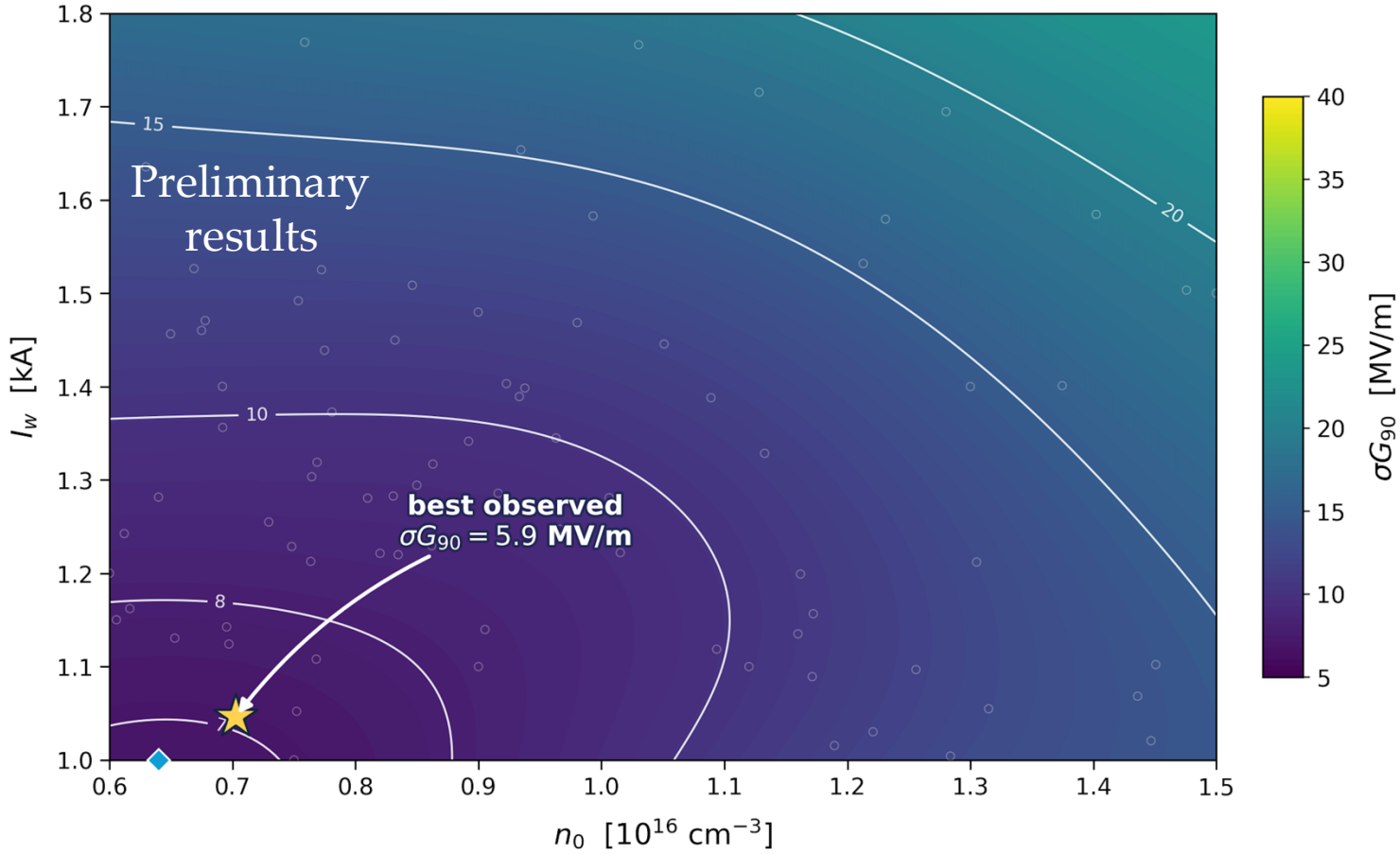
Future perspective:

1. **Bayesian optimization** starting from the TDR working point
2. Explore parameters for a completely new working point
3. Repet **start-to-end** simulations
4. 3D simualtions (OSIRIS)
5. Digital Twin (WP of EuPLASMAR project)



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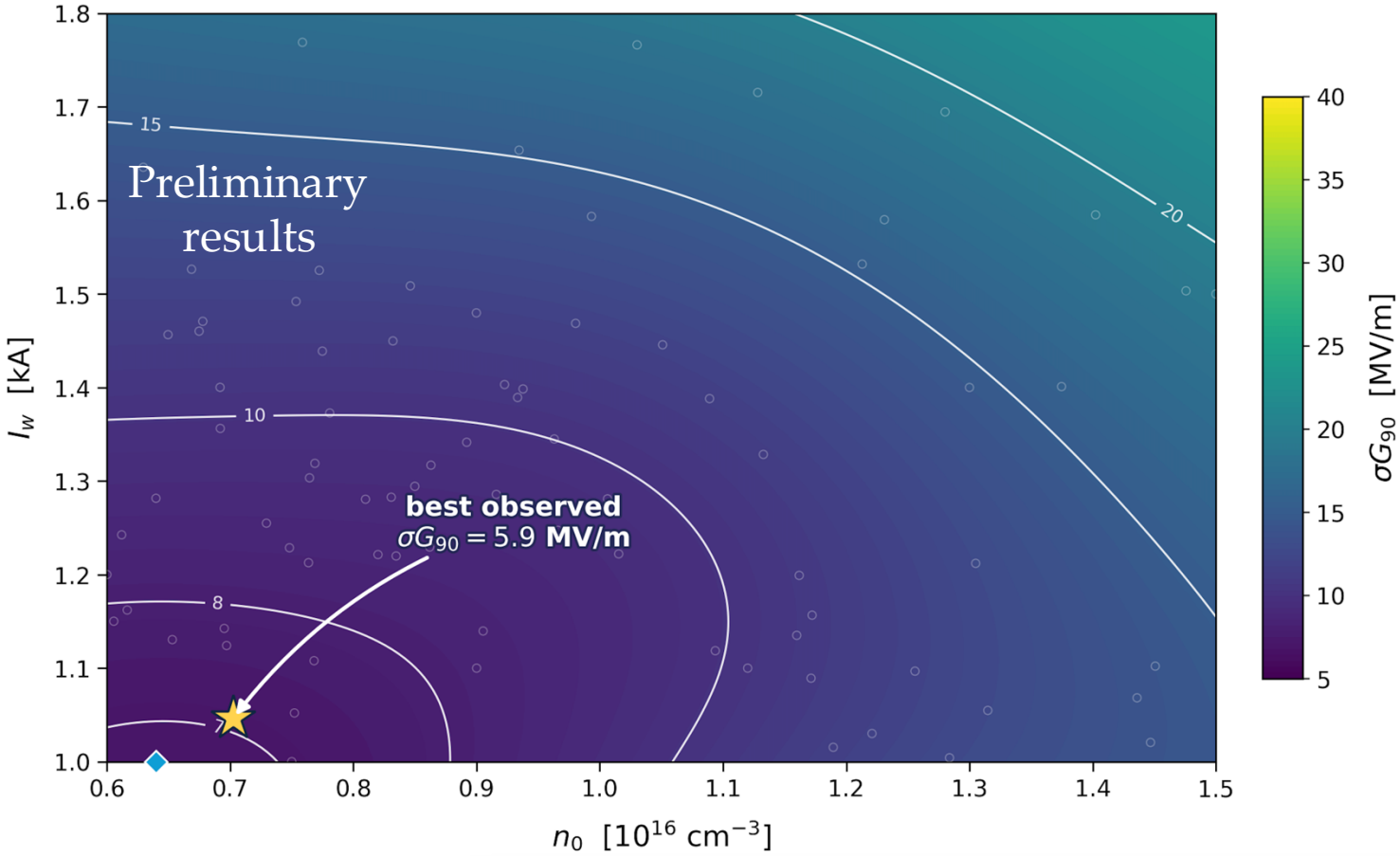

EuPRAXIA-PP Consortium

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Coordinator

Consiglio Nazionale delle Ricerche

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INFN Istituto Nazionale di Fisica Nucleare

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EuPRAXIA-PP Structure

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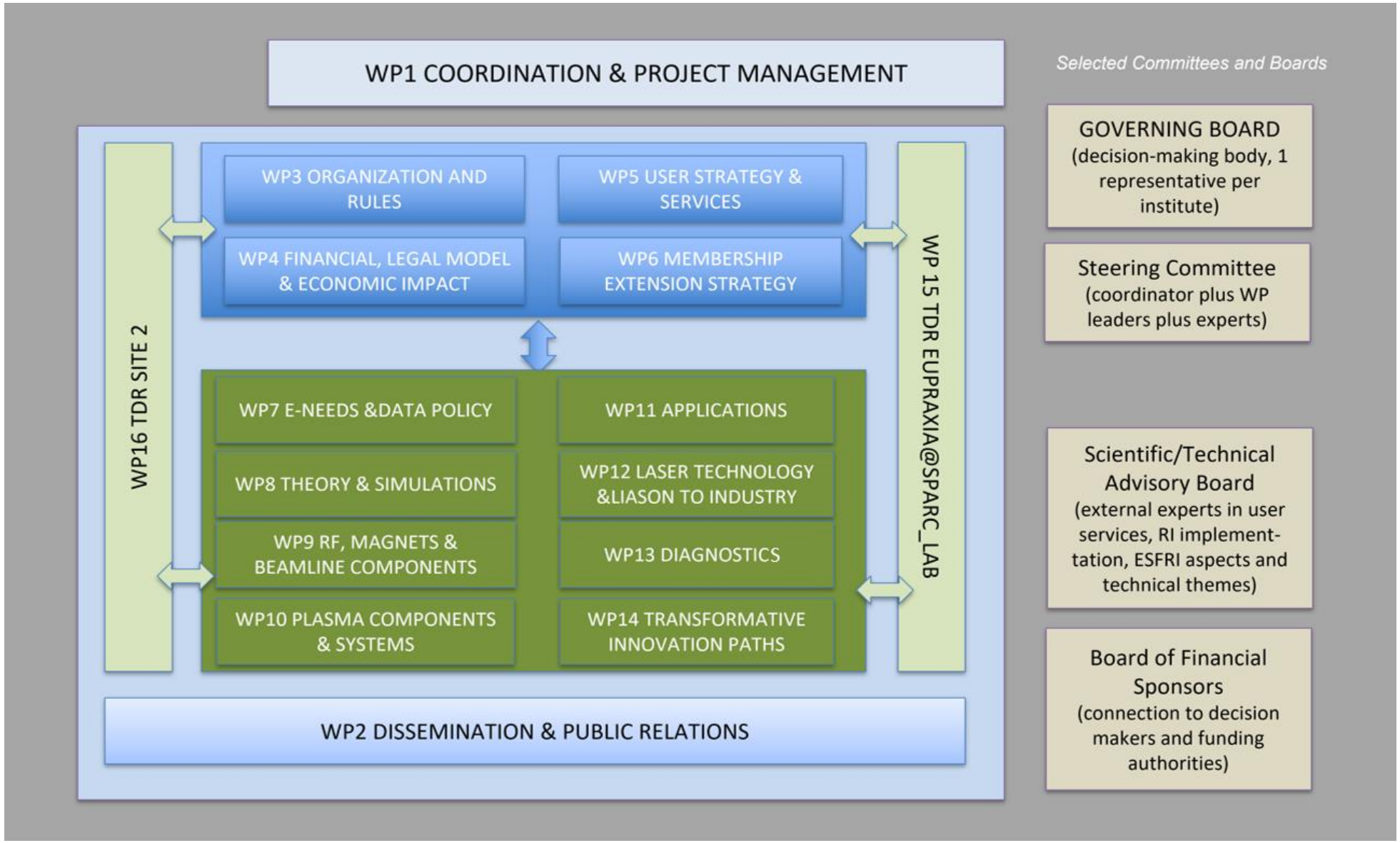

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EuPRAXIA Doctoral Network

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EuAPS

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Back slides

Resolution Study

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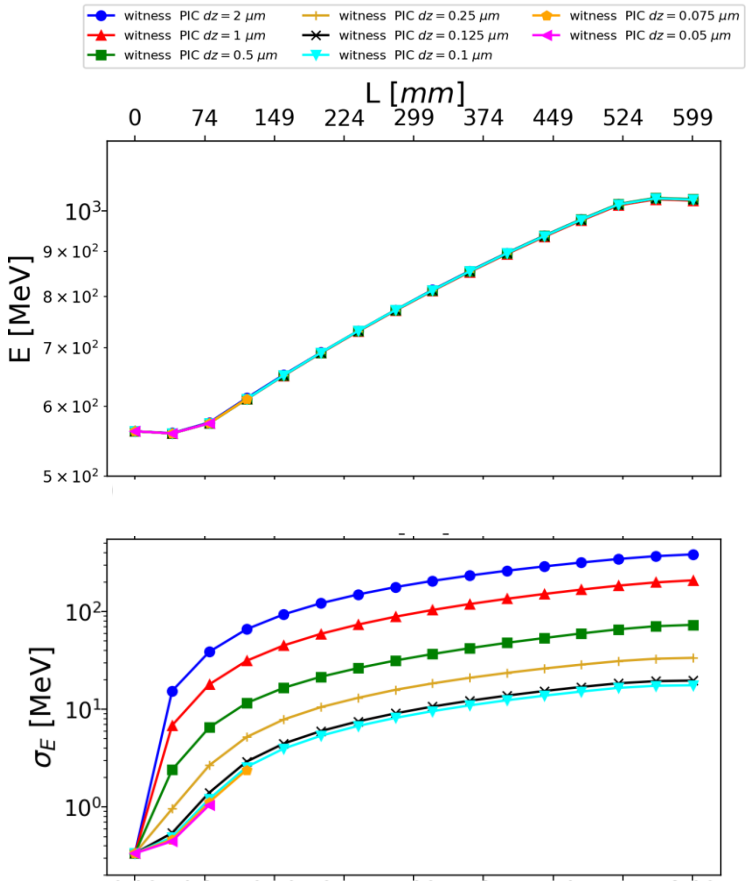

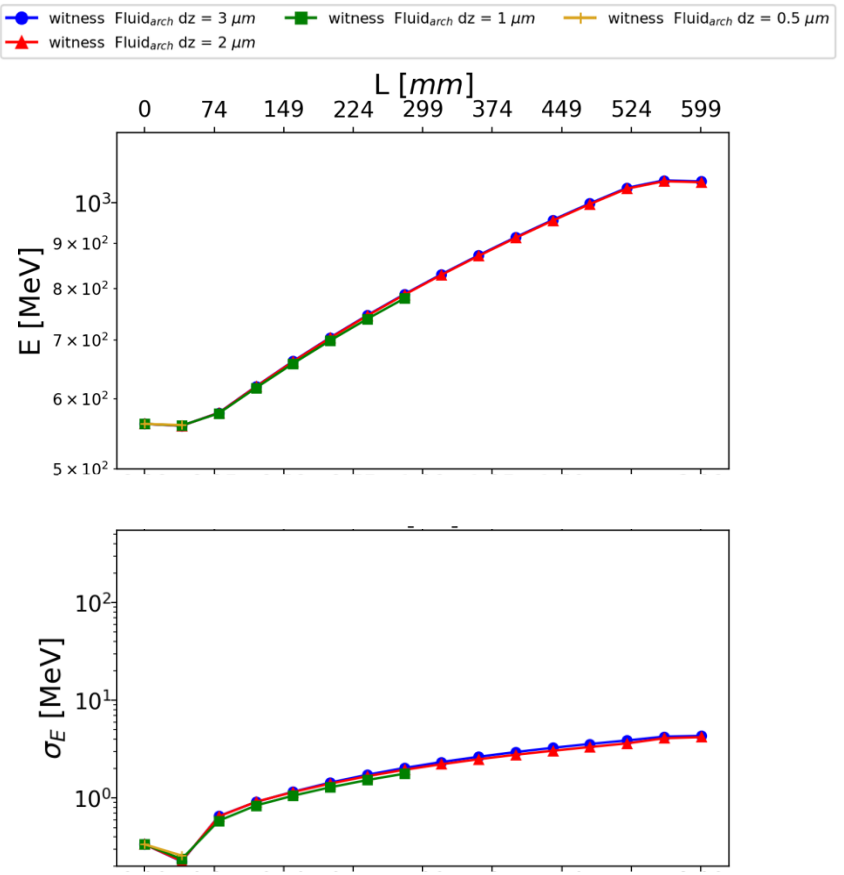

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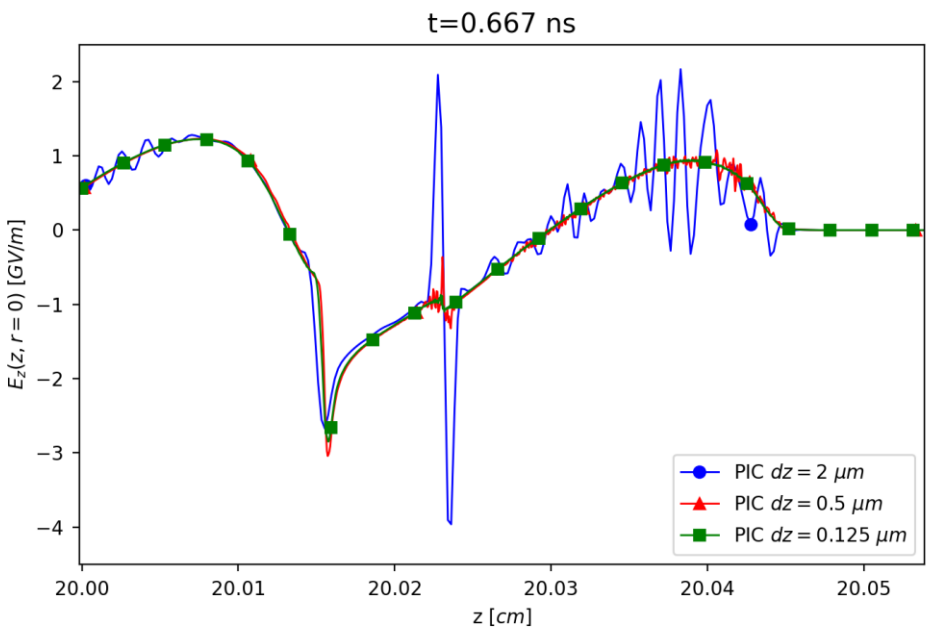

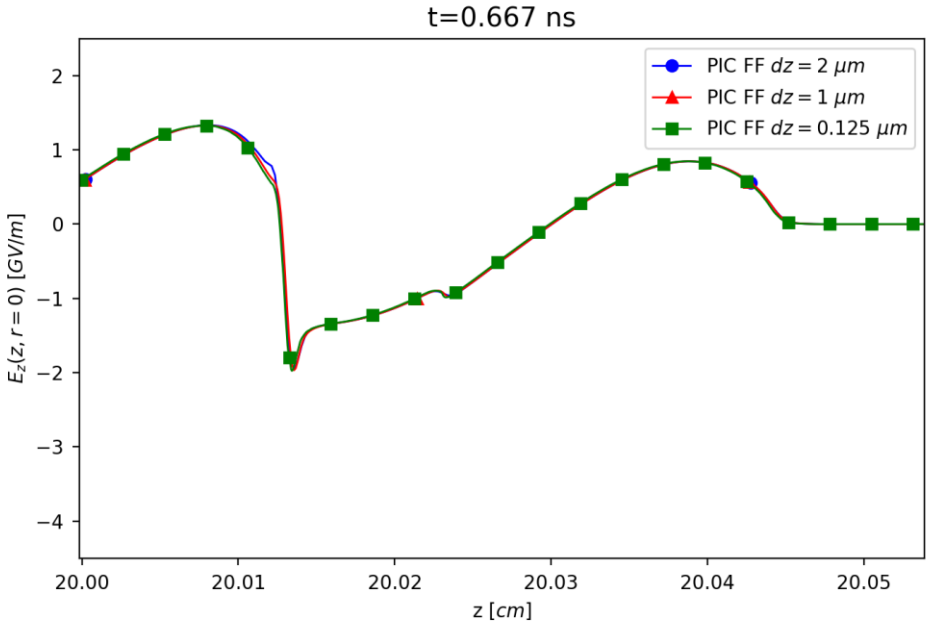

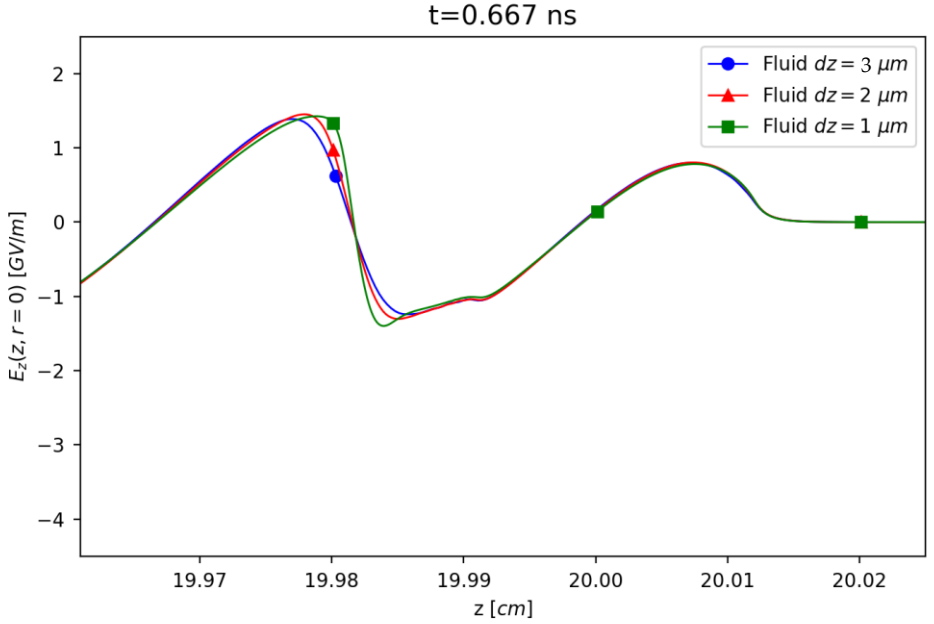

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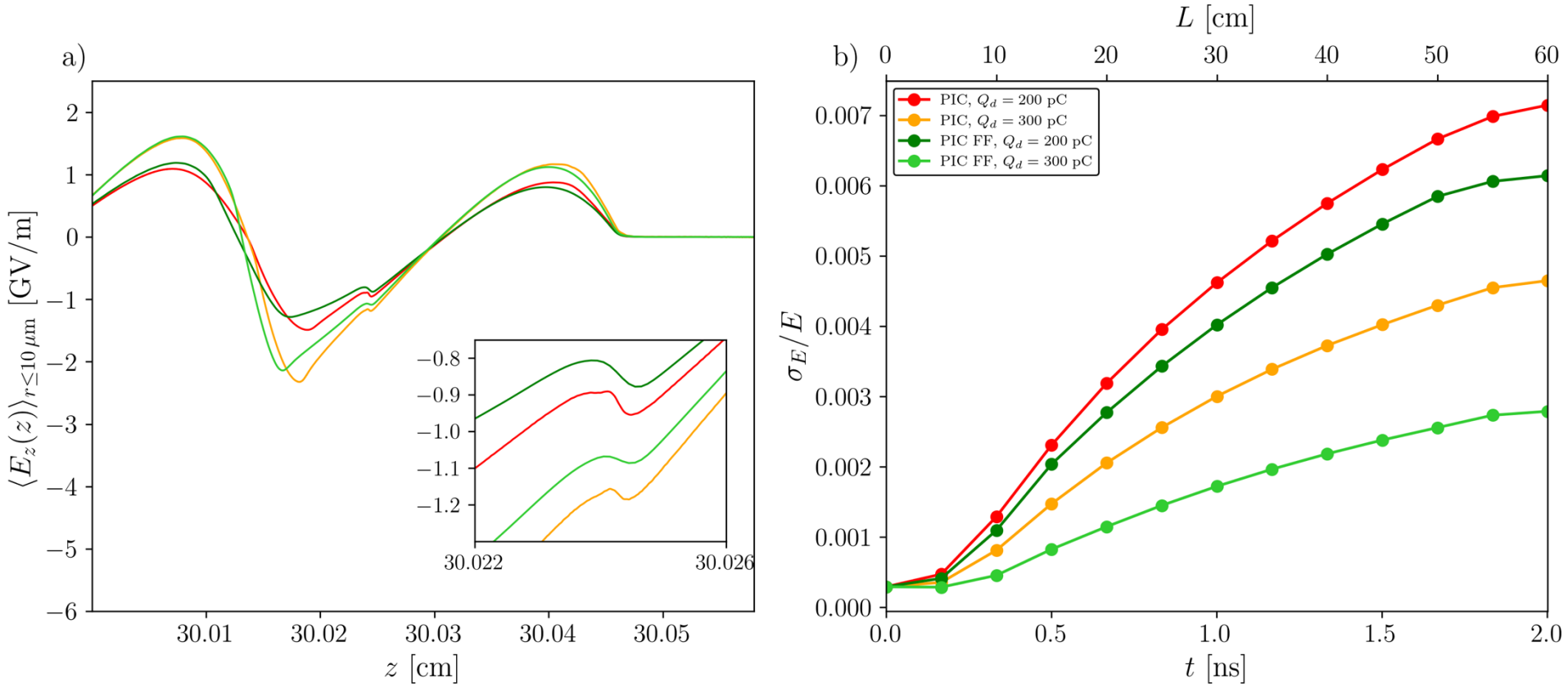

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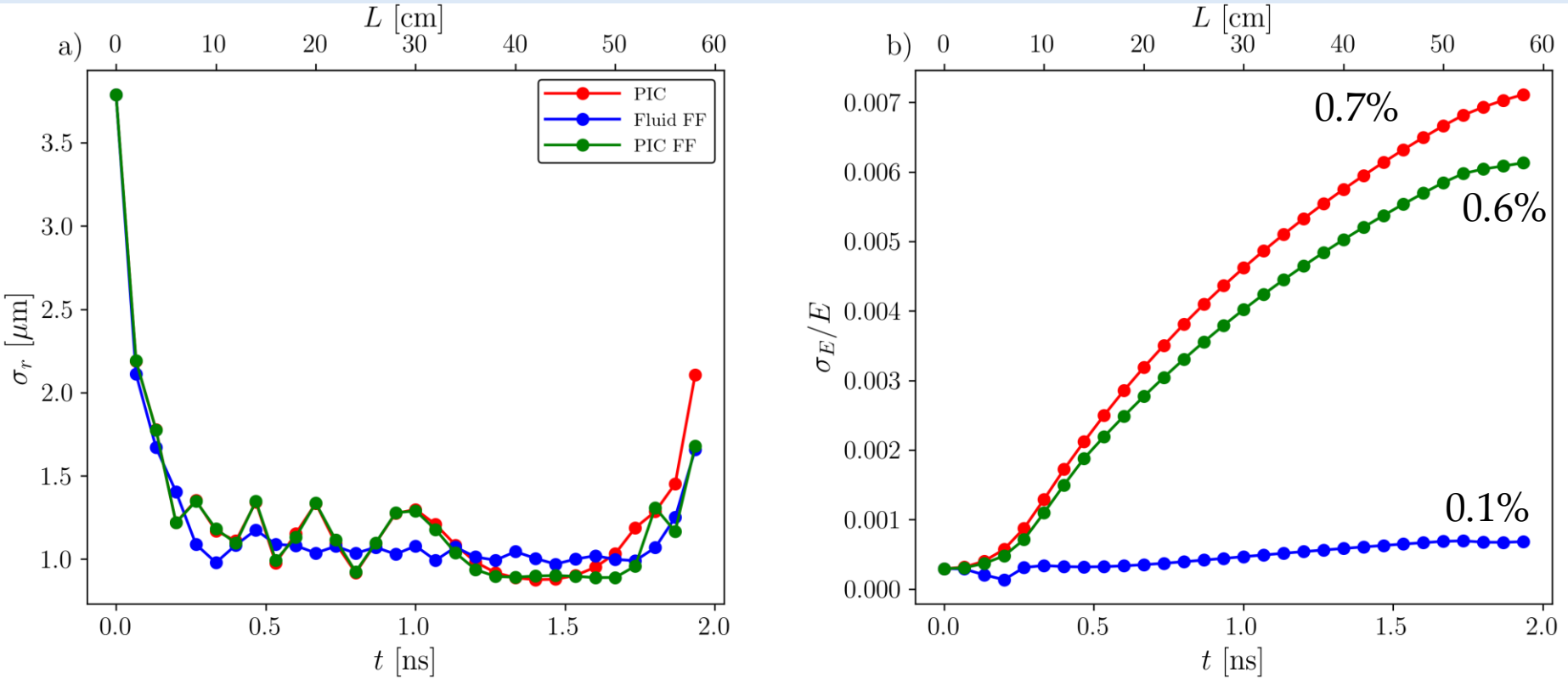
2. $0.6 < n0 < 1.5 \times 10^{16}$ [cm^{-3}] (E_z and $d_{d\text{-}w}$)
3. 0.5 ps < $d_{d\text{-}w}$ < $t(n_0)$
4. > 1 kA (FEL requirment)

Transverse dynamic and spread growth

Funded by the European Union



- ✓ The **working point is the same for all the models** (same driver and witness from TDR)
- ✓ To have another comparison, we used a Lu-Golovanov (Lu-Gol) analytical model to compute r_b and E_z
- ✓ The density color map shows two bubbles with different lengths and radii
- ✓ The main difference is in the **witness beam loading** (inset figure b)
  1. PIC → overloading
  2. Fluid → correct loading
- ✓ Transverce dynamic is similar → the match is correct with both models
- ✓ The overloading leads to an increase in energy spread