Plasma wakefield start to end acceleration simulations from photocathode to FEL with simulated density profiles

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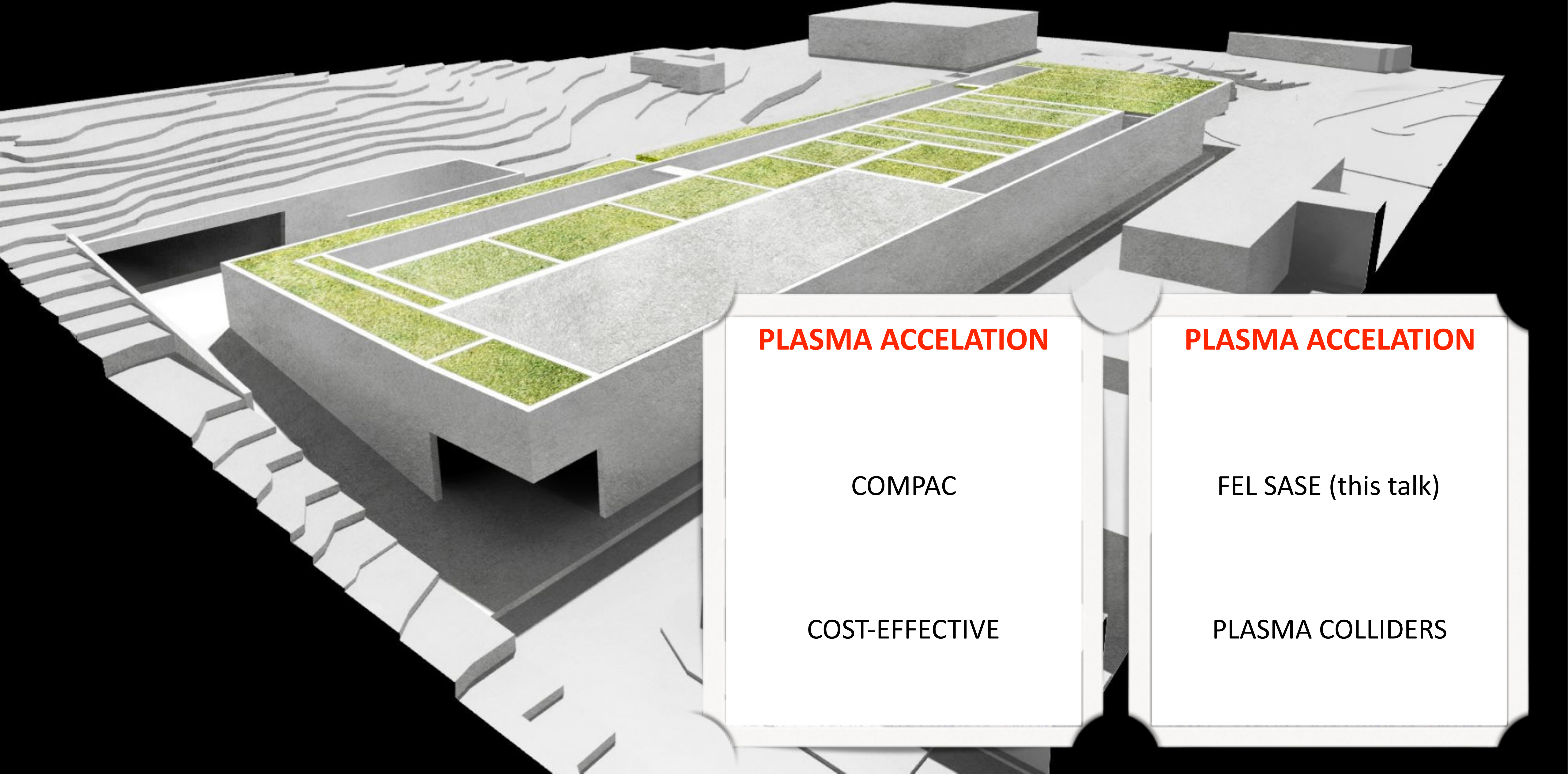
on behalf of the Sparc_Lab collaboration

picture by

EuPRAXIA@SPARC_LAB



PLASMA ACCELATION

COMPAC

COST-EFFECTIVE

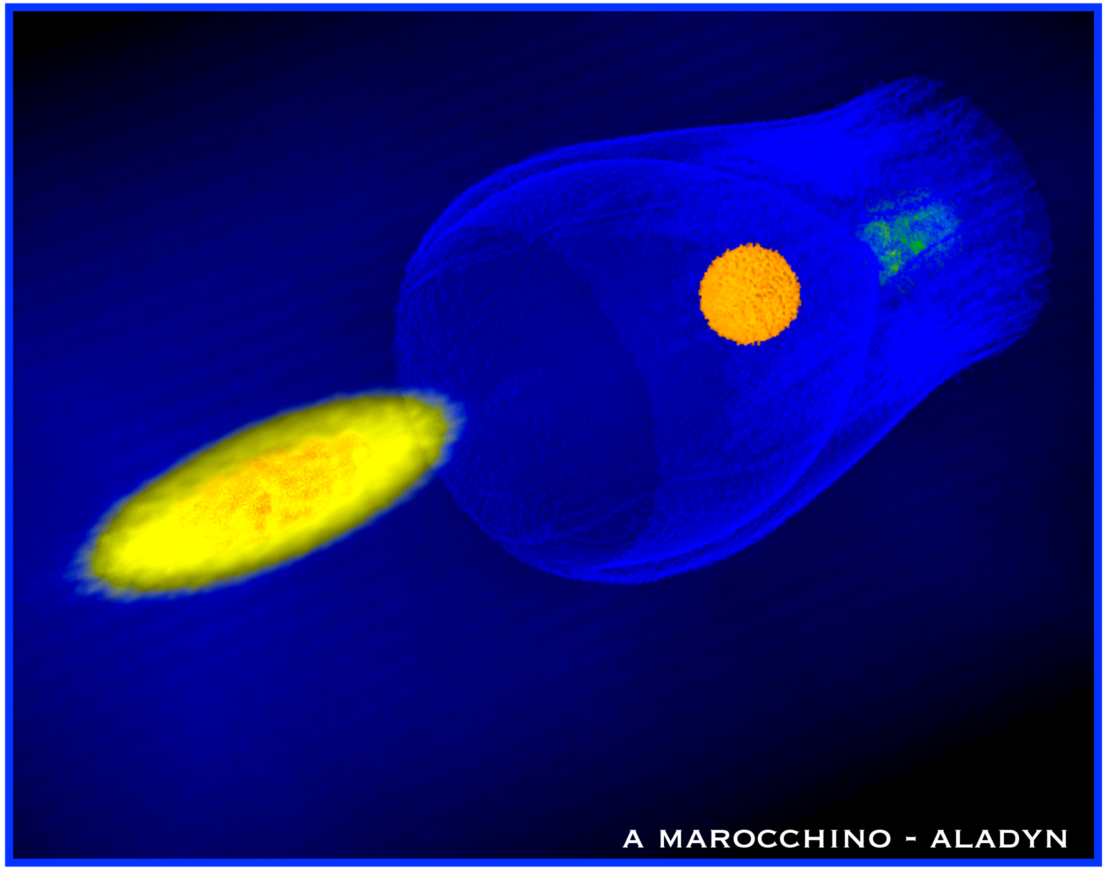
PLASMA ACCELATION

FEL SASE (this talk)

PLASMA COLLIDERS

Presentation Layout

- a realistic start-to-end simulation to pilot a FEL with a plasma accelerated bunch
- our codes:
  - PIC: ALaDyn and Architect
  - M-HD: DUED and Pluto

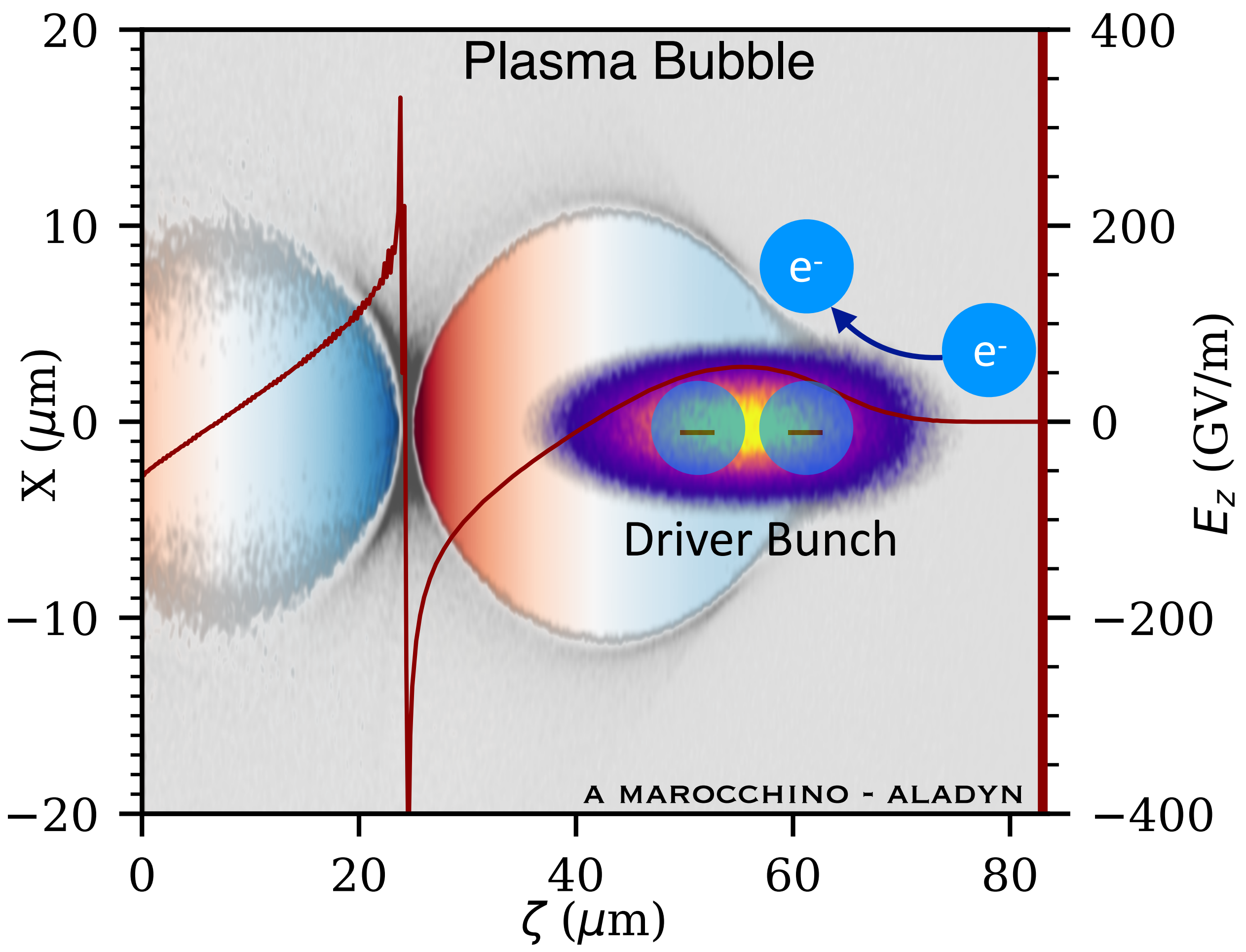


Beam Plasma Acceleration

Physics Mechanism

- Coulomb repulsion

Process Visualisation

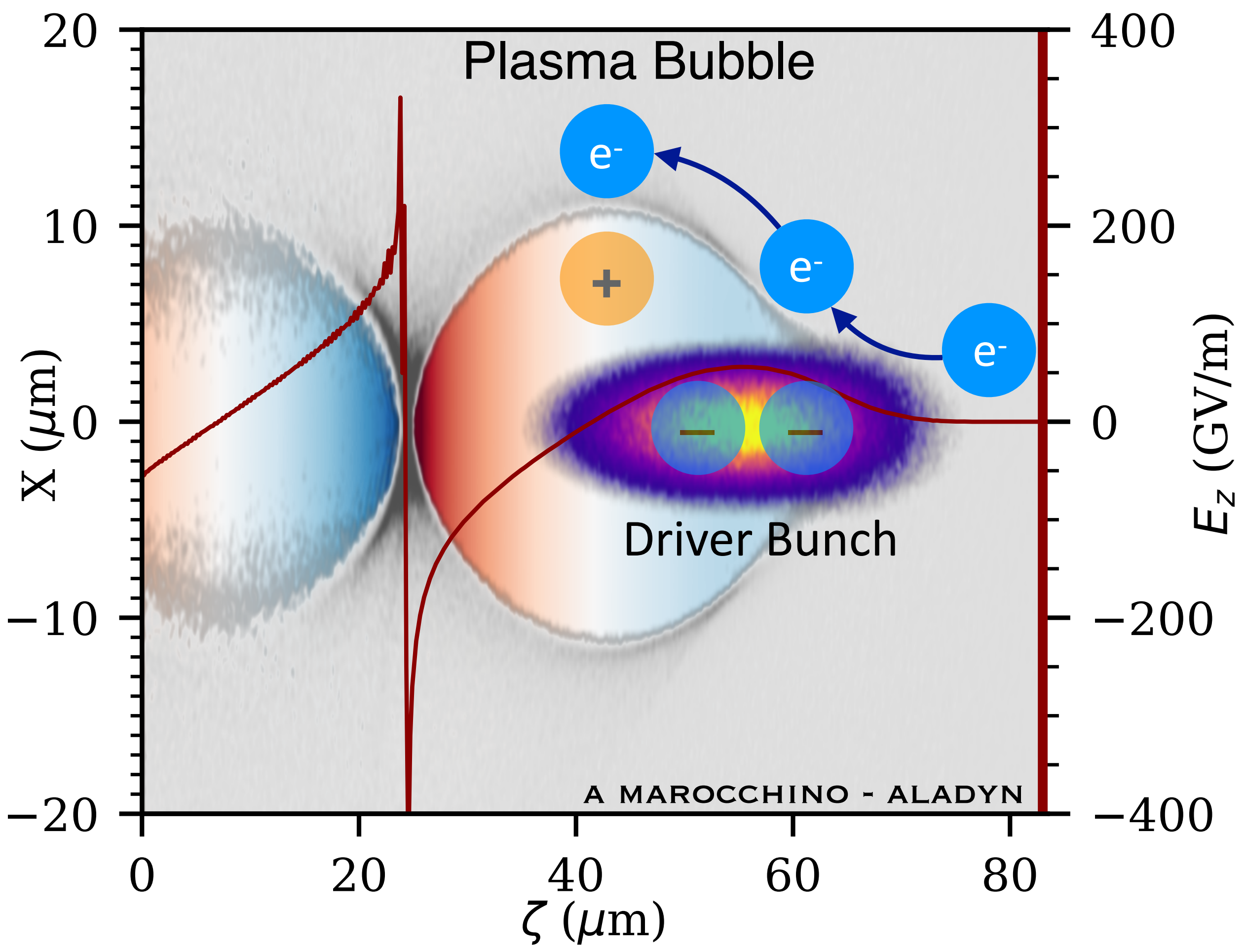


Beam Plasma Acceleration

Physics Mechanism

- Coulomb repulsion
- Bubble generation :: positive charge

Process Visualisation

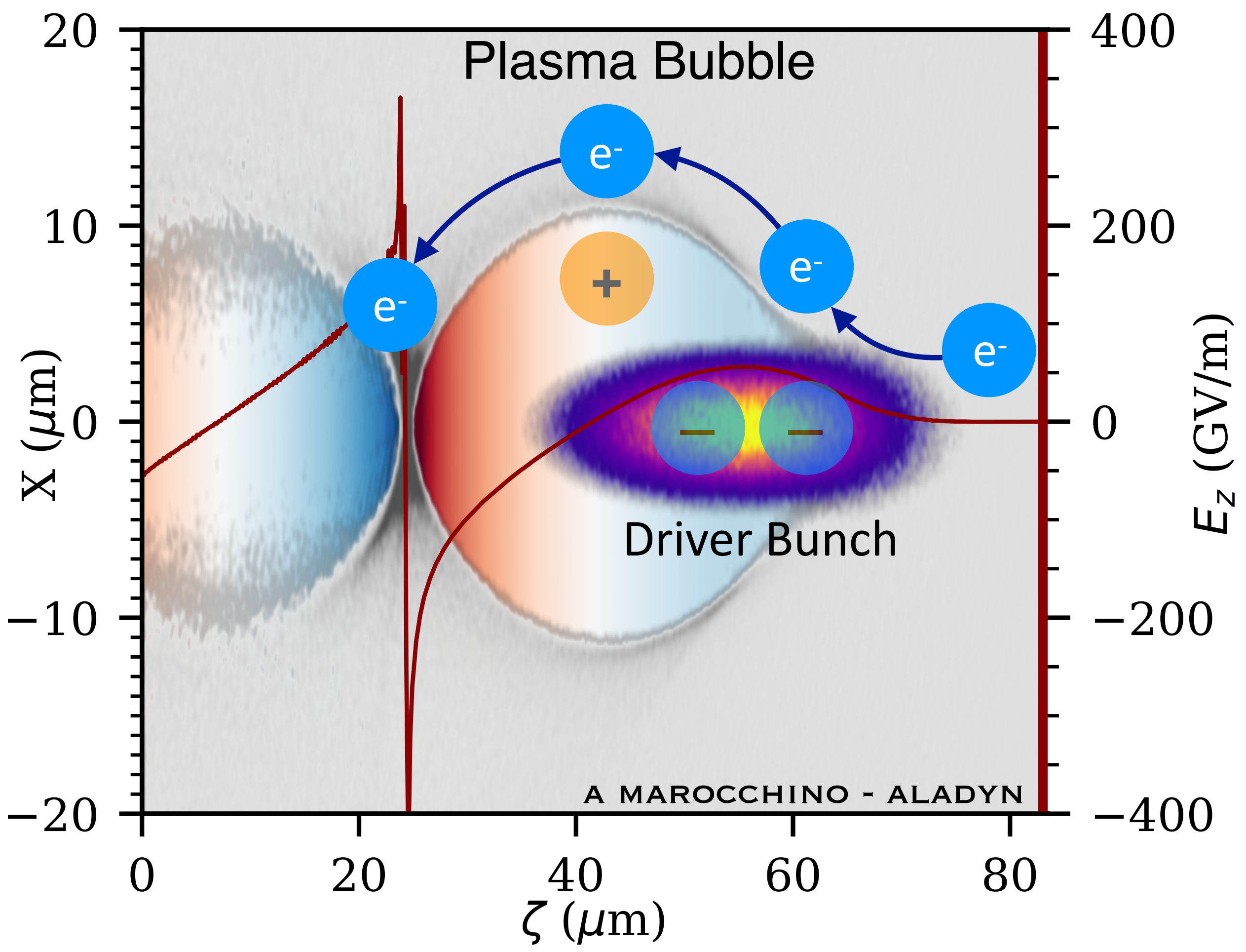


Beam Plasma Acceleration

Physics Mechanism

- Coulomb repulsion
- Bubble generation :: positive charge
- Coulomb attraction :: bubble closure

Process Visualisation

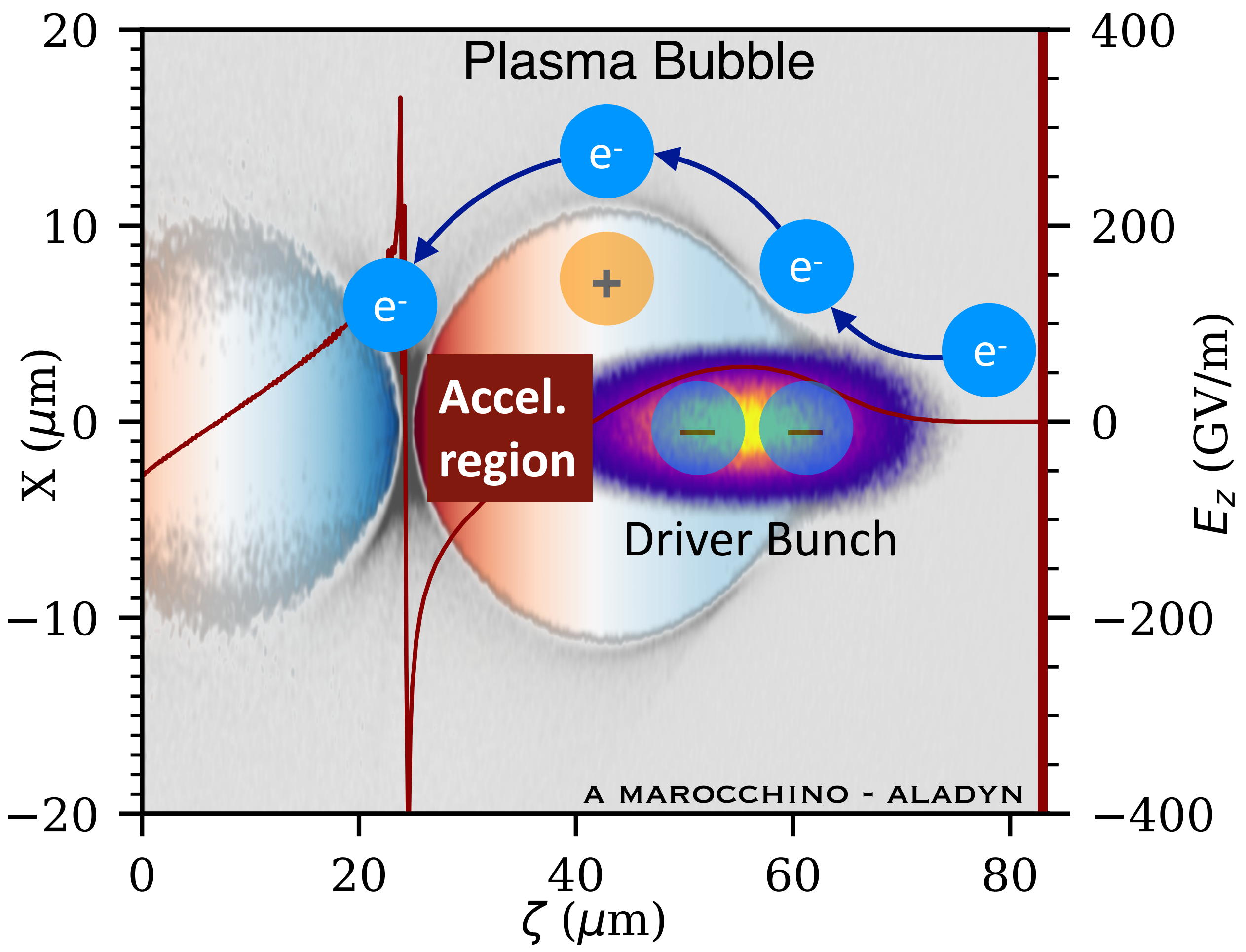


Beam Plasma Acceleration

Physics Mechanism

- Coulomb repulsion
- Bubble generation :: positive charge
- Coulomb attraction :: bubble closure
- the ion bubble generates a *strong* accelerating field

Process Visualisation



Plasma Acceleration Parameters

The Plasma dependance

- the bubble length:

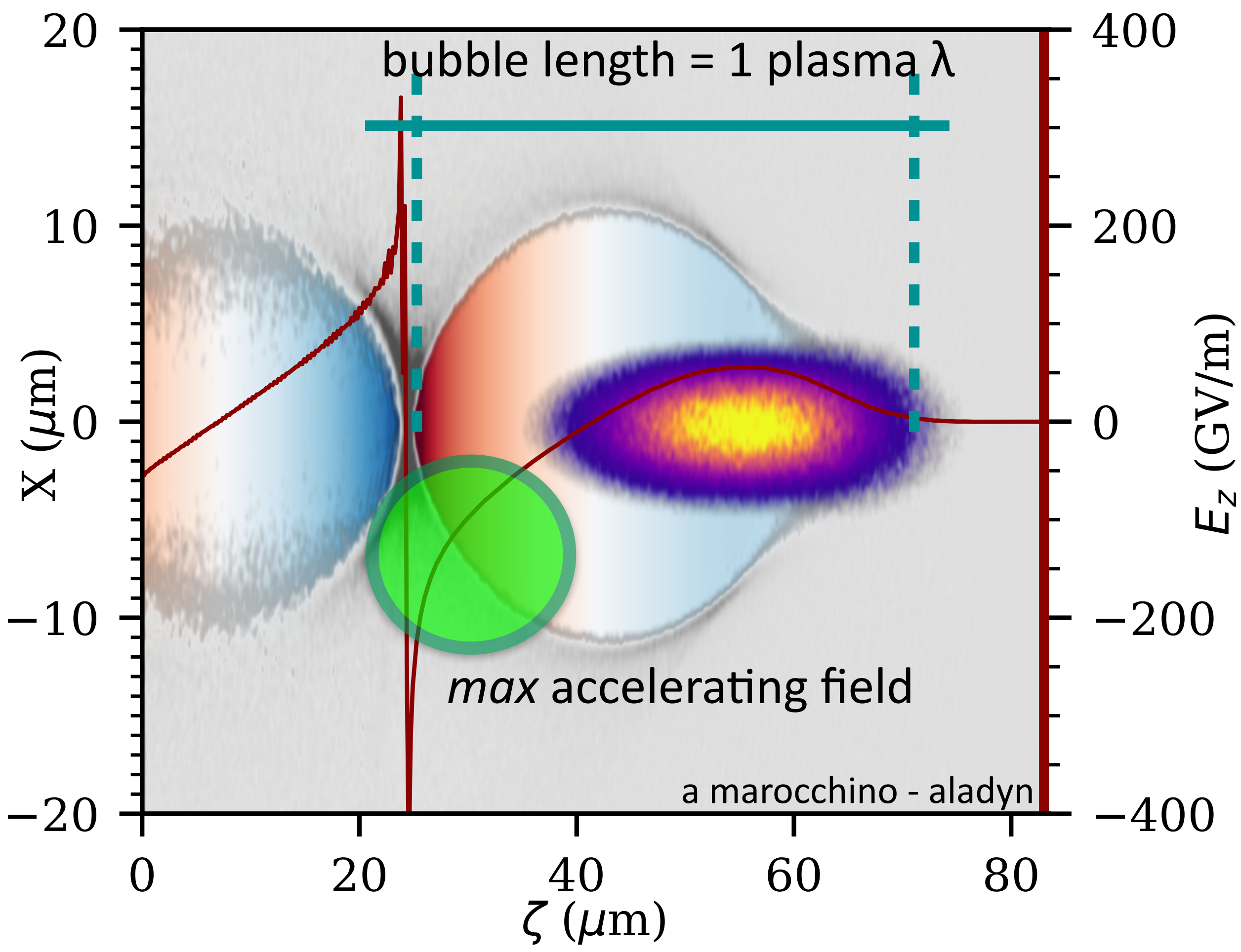
$$\lambda_p = 2\pi/\kappa_p = \sim 1/\sqrt{n_p}$$

- The maximum electric field:

$$E_{\max} \sim \sqrt{n_p}$$

(cm^{-3})	10^{16}	10^{17}
λ_p	330µm	104µm
E_{max}	10 GV/m	30 GV/m

our reference value



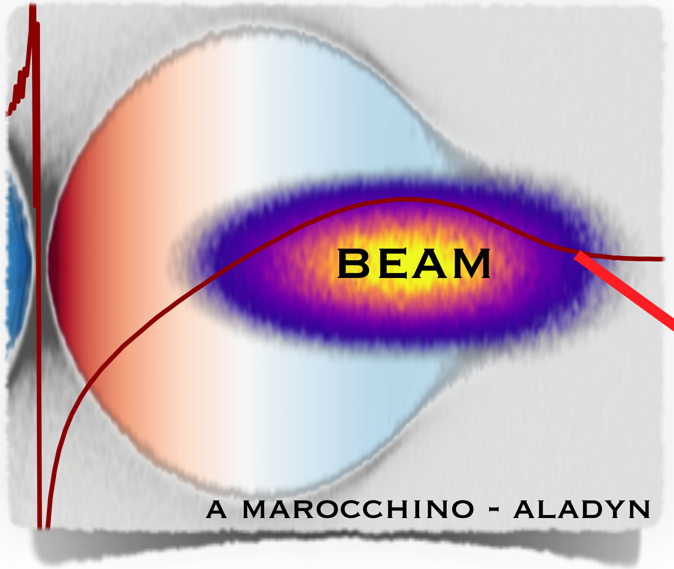
A. Marocchino et al. NIM-A 2018
DOI: 10.1016/j.nima.2018.02.068

Beam VS Laser Driven

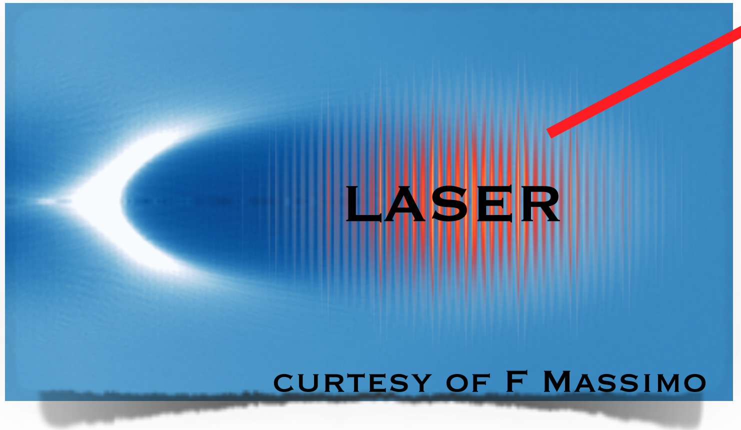
Plasma Wakefield Schemes

- the driver could either be: **our choice**
  - Laser Pulse
  - Charged bunch (electrons, positions, protons)

- Beam advantages:
  - longer depletion lengths
  - require no guiding
  - no driver-trailing bunch dephasing
  - higher energy transfer

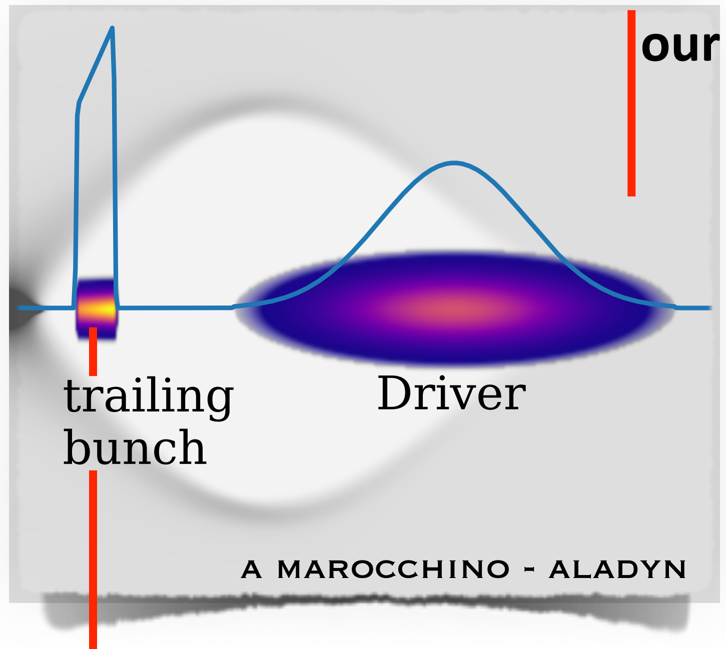


Drivers



external VS internal injection

external



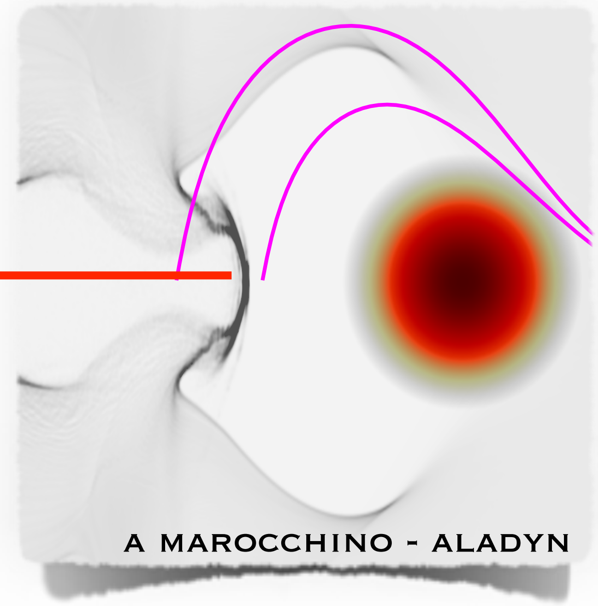
- externally produced (photo-injector)
- placed right phase
- higher degree of control
- generated with the required *shape* or *quality*

A. Marocchino et al. NIM-A 2018, DOI: 10.1016/j.nima.2018.02.068

internal

Generated internally by the plasma

e.g. by a density bump



- suffers from shot-to-shot large fluctuations (e.g. gas nozzle-blade)
- trailing bunch of *poor quality*

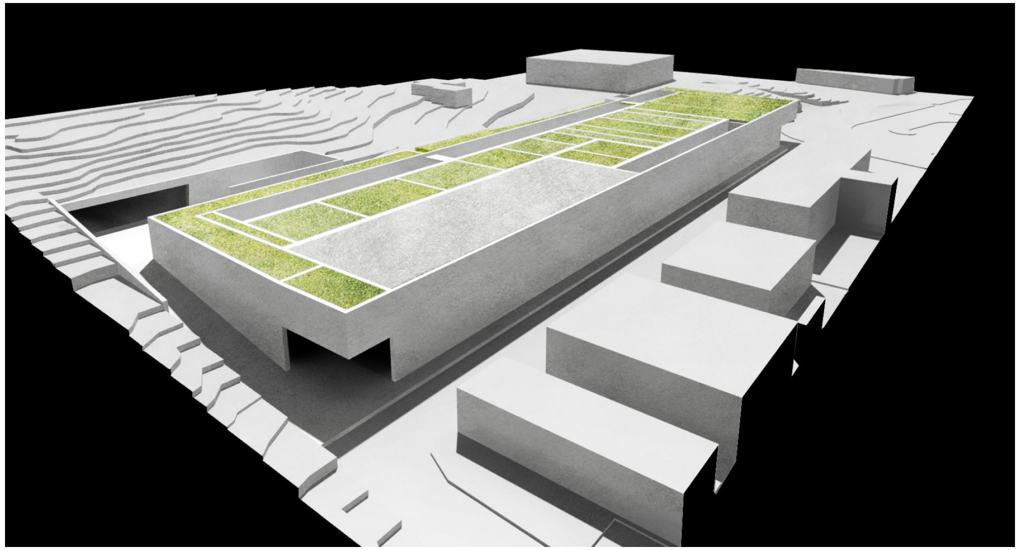
F. Mira - A. Marocchino et al. NIM-A 2018, DOI: 10.1016/j.nima.2018.01.019

EuPRAXIA@SPARC_LAB

- ***EuPRAXIA*** is an European project that ***will bridge the gap between successful proof-of-principle experiments and ultra-compact accelerators for science***

- **EuPRAXIA@SPARC_LAB** is the future Frascati-LNF facility for PWFA experiments
  a unique facility that is being built on 3-pillars:
  - large plasma **accelerating gradients**
  - acceleration with **little trailing bunch depletion**
  - **FEL piloting** with a plasma accelerated bunch

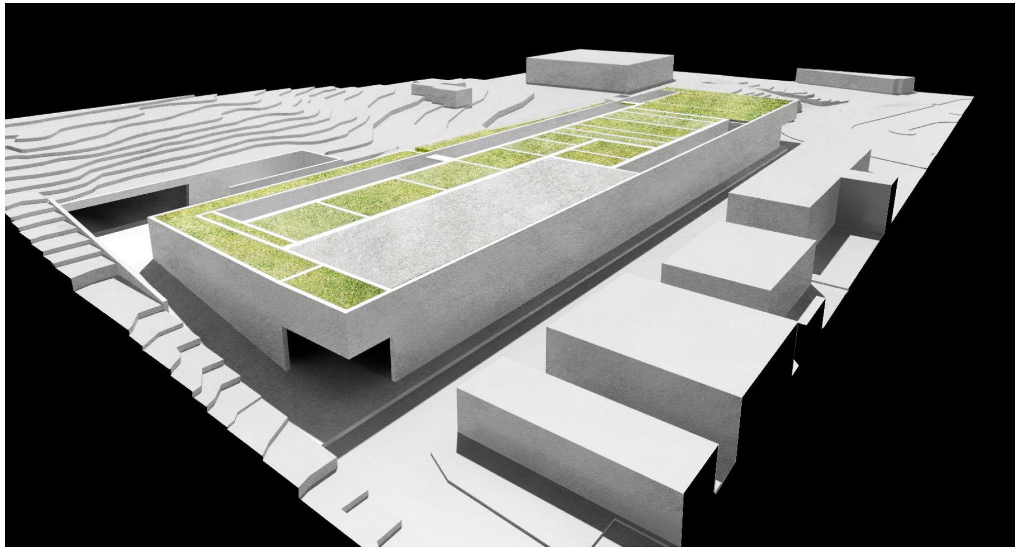
- leveraging on established know-how:
  - beam dynamics
  - beam-plasma-codes



EuPRAXIA@SPARC_LAB conceptual design report arXiv and LNF Publishing

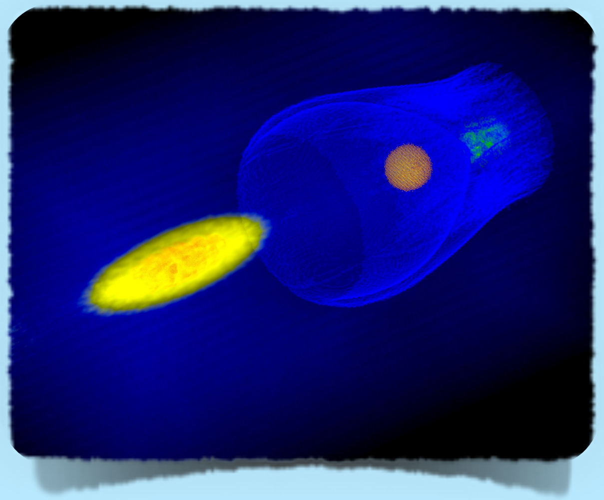
EuPRAXIA@SPARC_LAB

Parameter Choice - pillars	
1 GeV FEL	water window
X-band	compact - research RF tech
plasma acceleration	high gradient acceleration
external injection	highly controllable and tunable



EuPRAXIA@SPARC_LAB conceptual design report arXiv and LNF Publishing

PWFA Numerical Codes

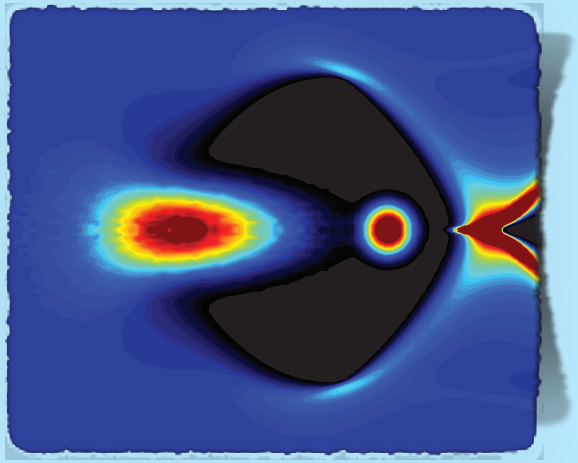


ALaDyn

full PIC code

bunch and background treated with macro-particles

latest PWFA version:
A. Marocchino et al. NIM-A 2018
DOI: 10.1016/j.nima.2018.02.068



rchitect

hybrid code

bunch treated as a PIC background as a fluid

latest PWFA version:
A. Marocchino et al. NIM-A 2015
DOI: 10.13140/RG.2.1.4072.9041

Sharing-Chatting via the most modern socials *(please join!)*

Architect

- **Bunch**(es) are treated **kinetically**
- **background plasma as a fluid**
- systematic scan
- run time
- no-Quasi Static Approximation

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

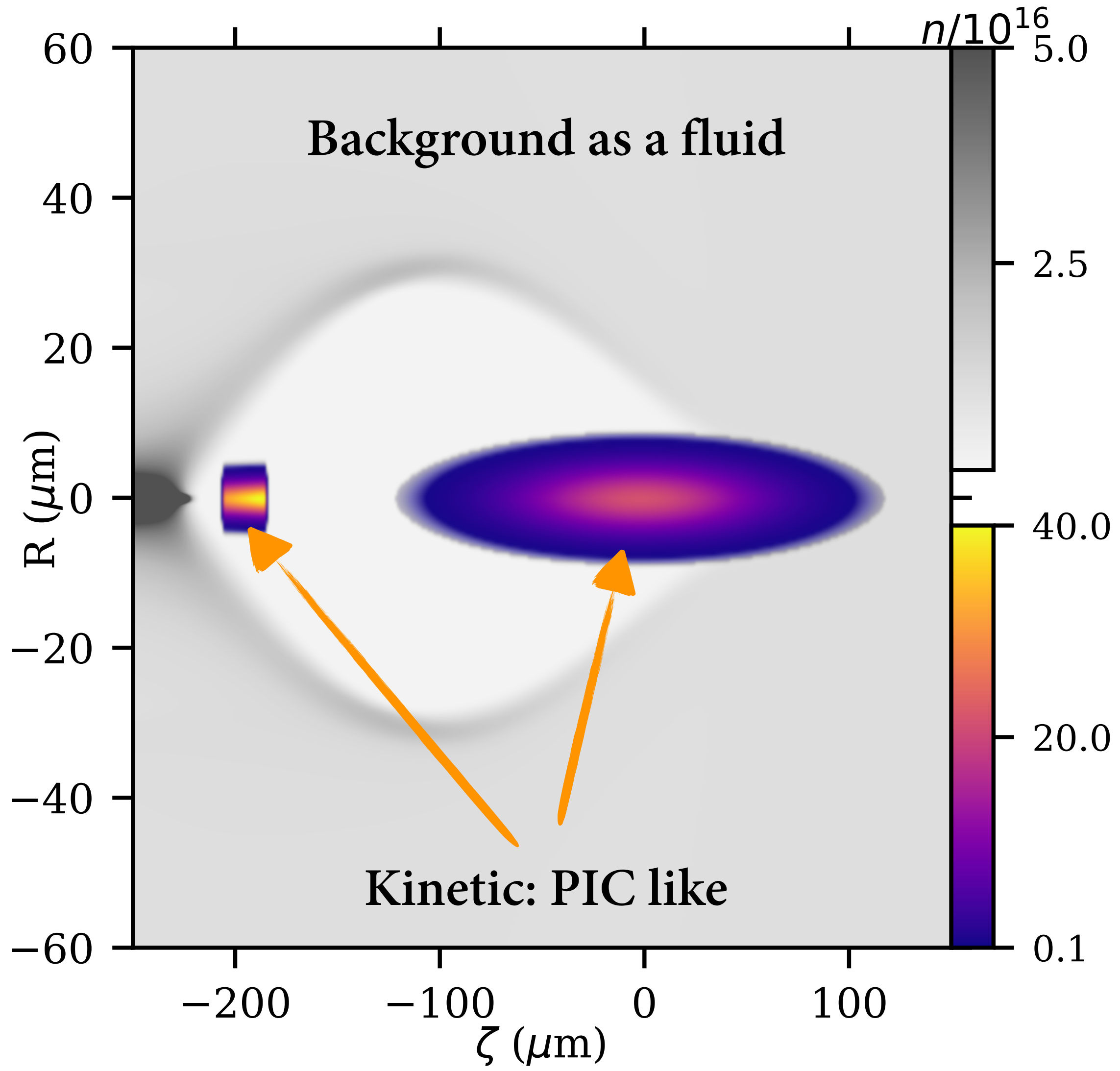
$$d_t \mathbf{x}_{\text{particle}} = \boldsymbol{\beta}_{\text{particle}} c$$

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

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

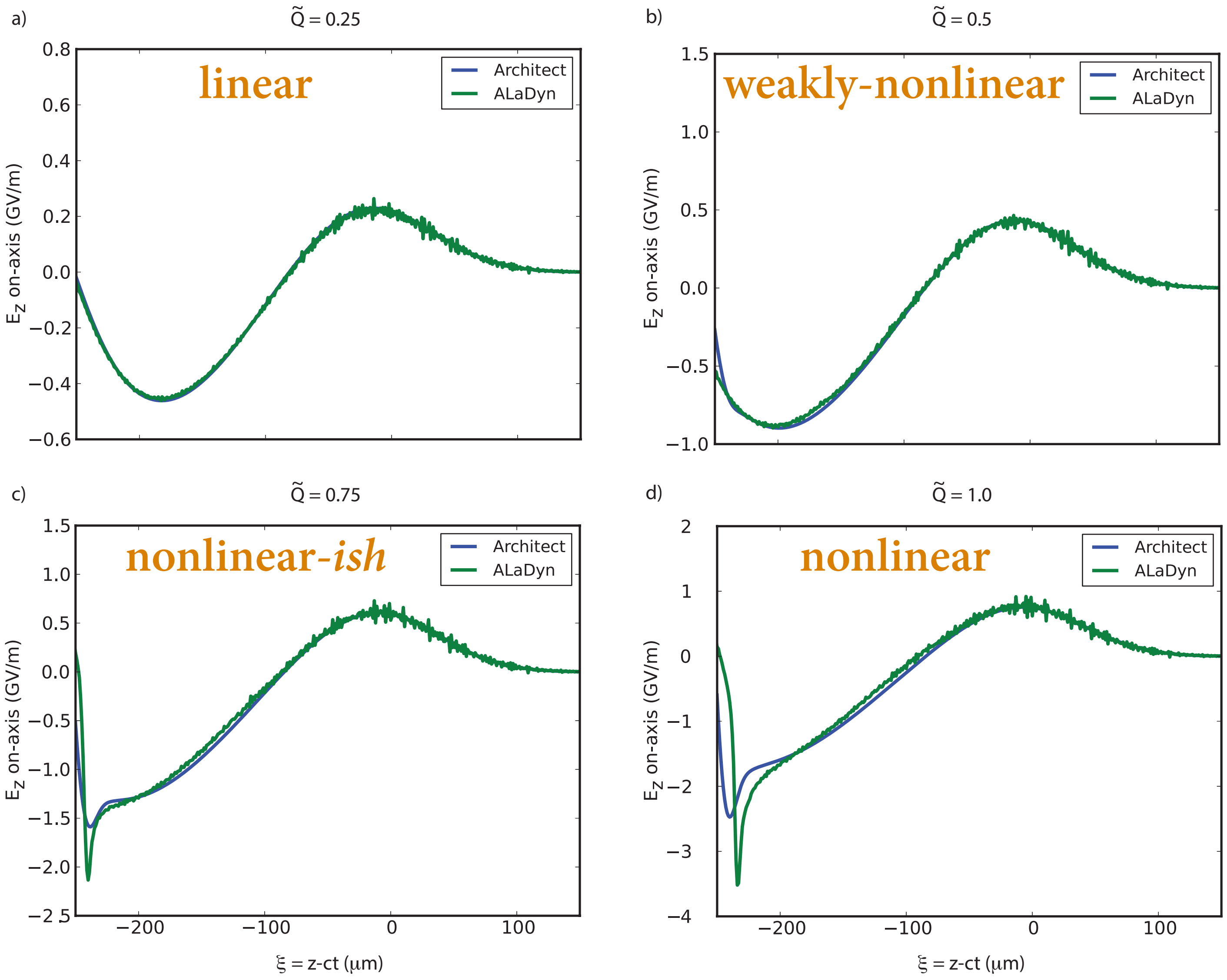
$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$

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



Architect VS ALaDyn

- Comparison:
  - **ALaDyn** VS **Architect**
  - Different regimes
- good agreement up to nonlinear
- the disagreement occurs in the bubble closure (kinetic) region

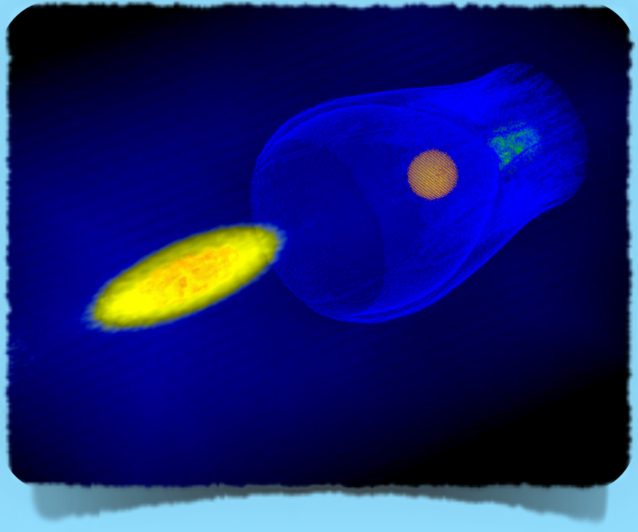


F. Massimo - A. Marocchino J. Comp. Phys. 2016
DOI: 10.1016/j.jcp.2016.09.067

ALaDyn

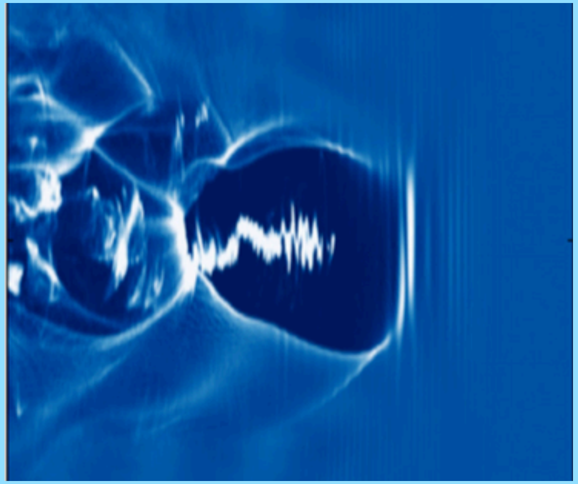
an open source code

http://github.com/ALaDyn



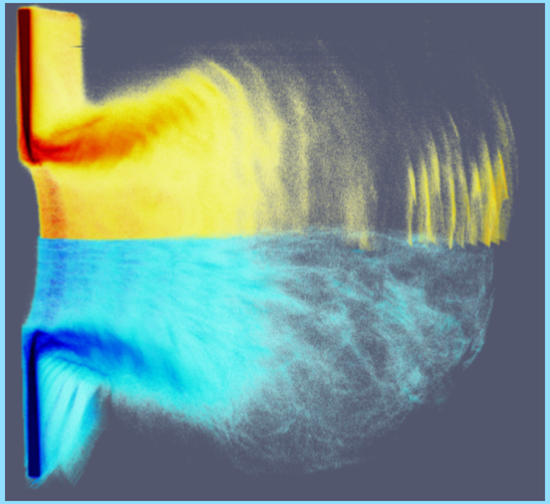
PWFA

- Roma



LWFA

- Pisa
- Roma
- Bologna

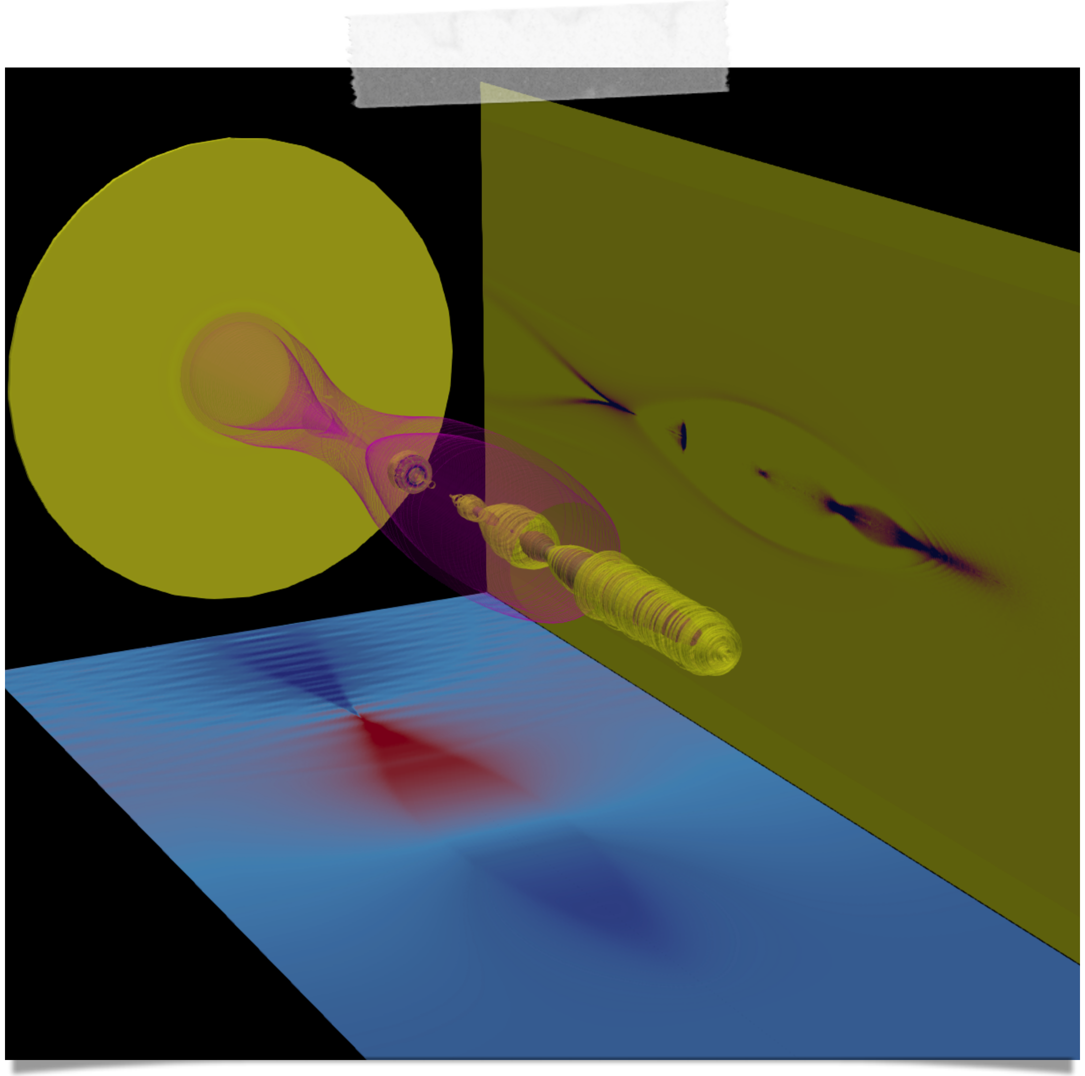


TNSA

- Pisa
- Bologna

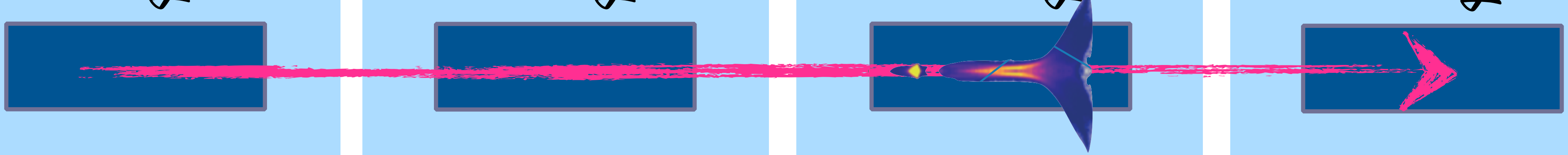
ALaDyn

- Plasma and Laser Wakefield acceleration
- Fully kinetic
- Fully explicit
- Fluid background (*in progress, Architect style*)
- Bunch Particles
    - Equal Charge
    - Weighted Option
- Ionisation modules: ADK and BSI
- Envelope approximation
- Fortran <-> *interfaced* <-> c++
- python interfaced and *controllable*
- 3D visualisation with VTK



from Photo-Injector to FEL

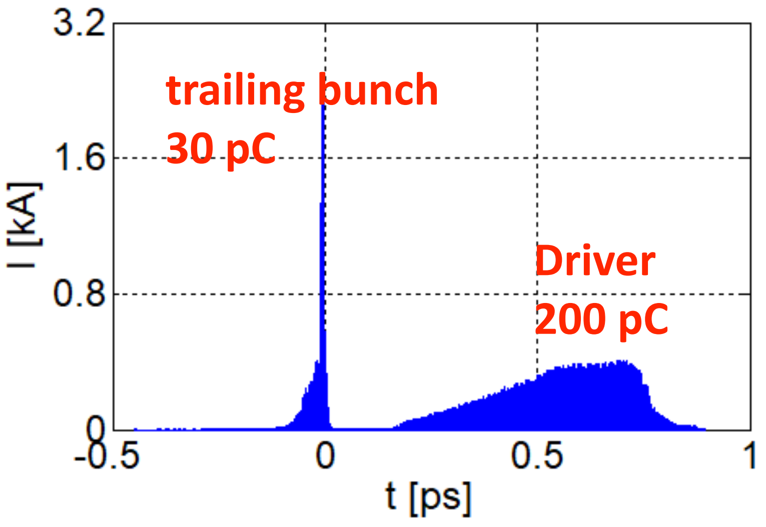
I stage	*II stage*	*III stage*	*IV stage*
photo injector	RF linac X-band	plasma acceleration	Free Electron Laser
bunch generation	bunch pre-acceleration to 500 MeV	bunch acceleration to 1 GeV	FEL piloting and lasering



Conceptual design report by the SPARC_LAB group

bunch generation

bunch currents :: TStep sims



- Trailing bunch triangular shape
- Bunch separation 0.55 λ_p :: accelerating phase
- 2 kA peak current

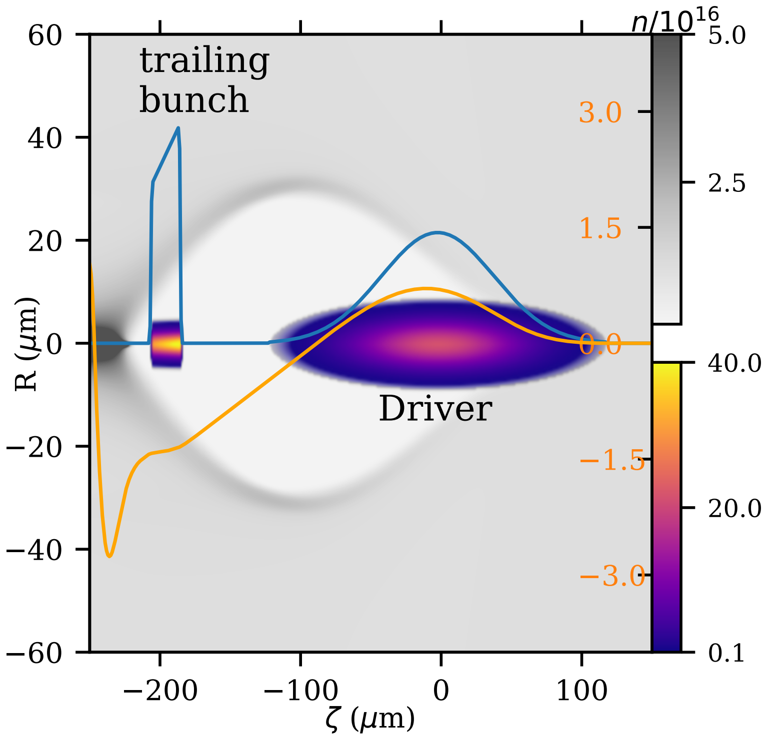
A. Giribono et al. NIM-A 2018

trailing bunch quality

	Tr. Bunch
Charge	30 pC
Energy	101.5 MeV
RMS Energy	0.15%
σz	3.6µm
peak current	2 kA
εx norm	0.69 mm-mrad

- high brightness bunch
- little deterioration after the comb compressing reversing technique

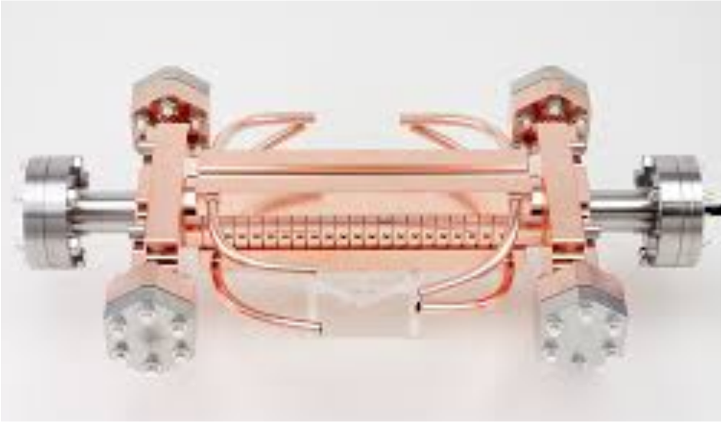
bunch parameters



- beam loading compensation

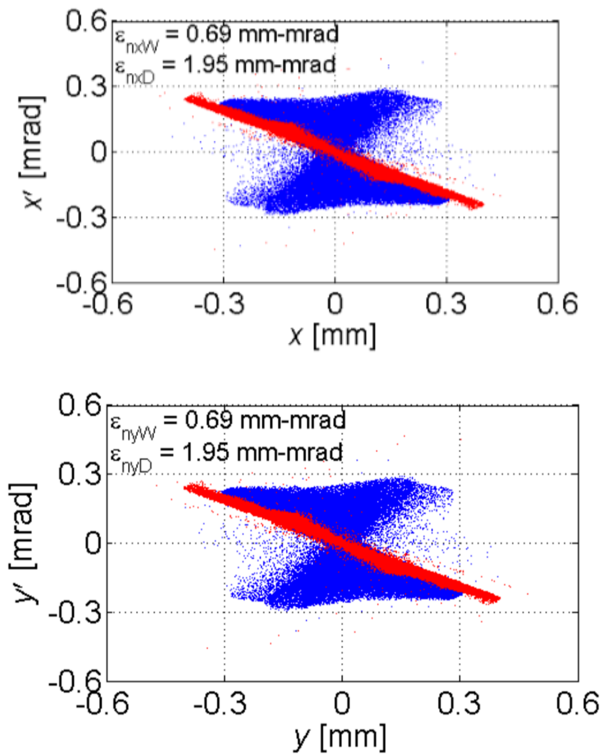
X-band

The *X-band* linac

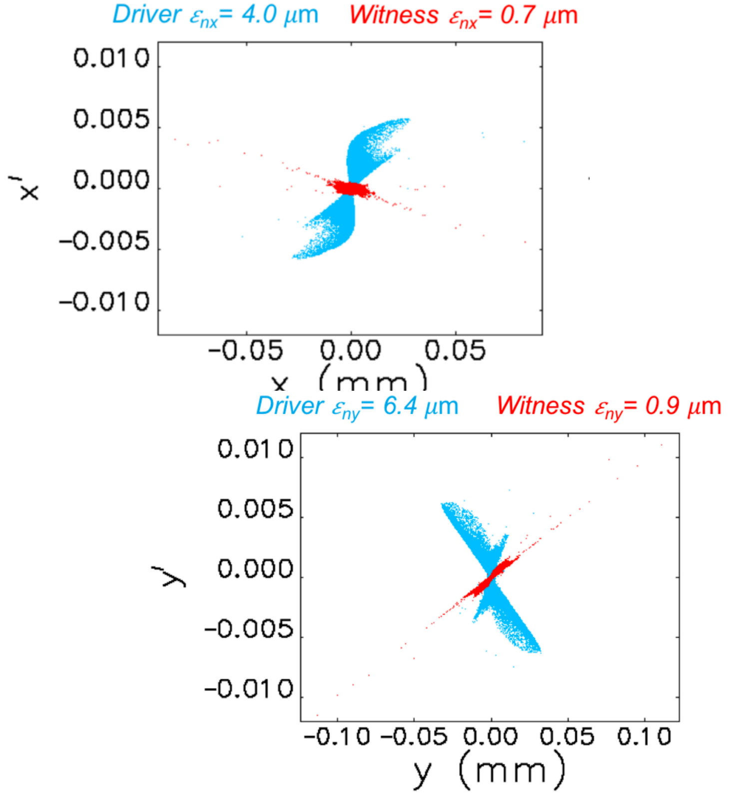


- Accelerating gradient: 60 MV/m
- each section is 50 cm long
- 32 sections
- iris diameter 3.2 mm

from ~100 MeV



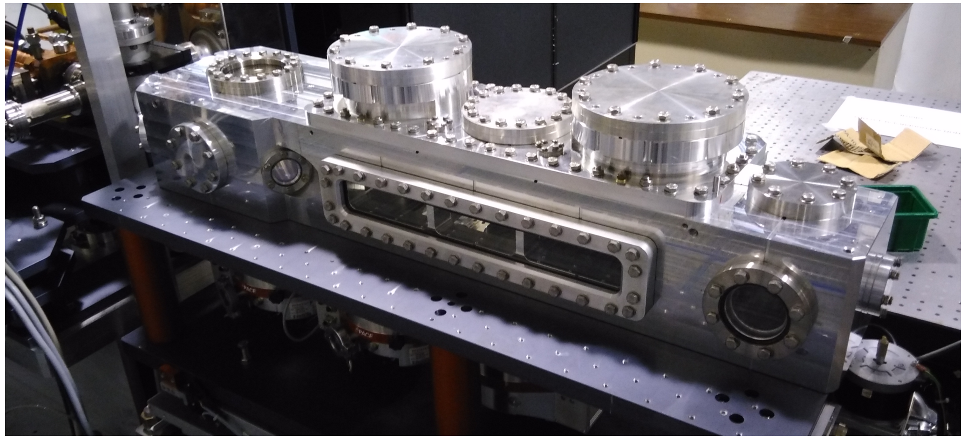
to ~500 MeV

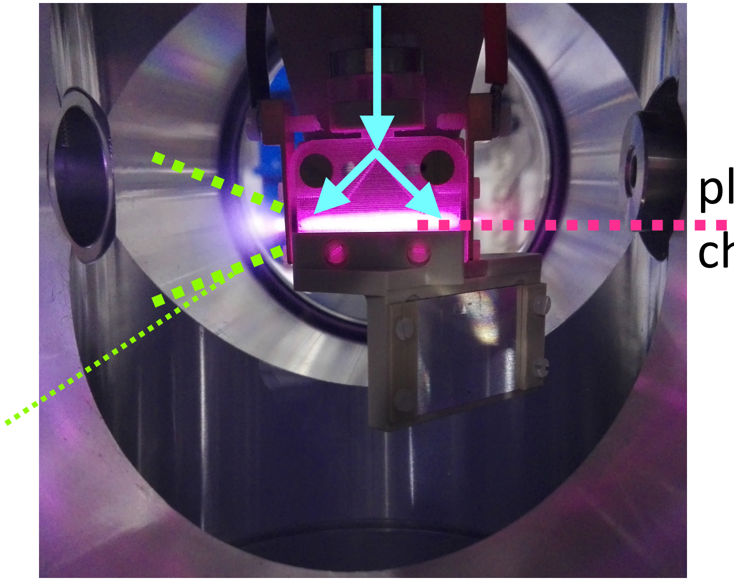


it is difficult to tune the machine for the Driver and the trailing bunch at the same time. Our main focus in the trailing bunch.

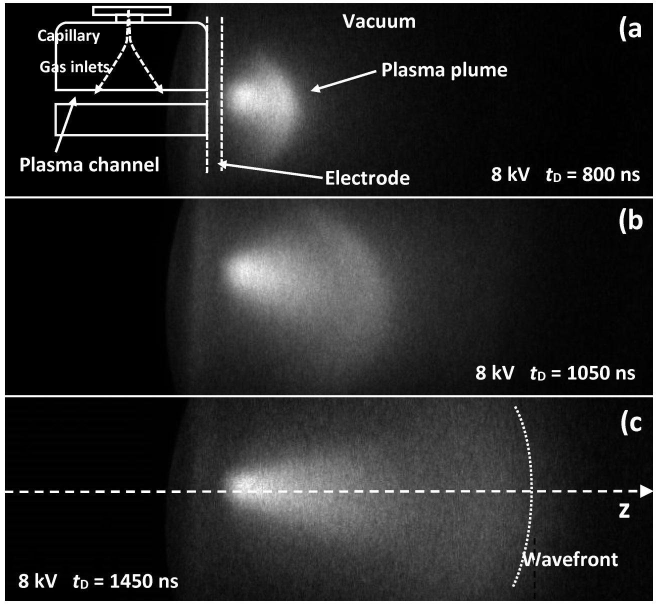
C. Vaccarezza et al. NIM-A 2018

plasma acceleration capillary





plasma ejecta

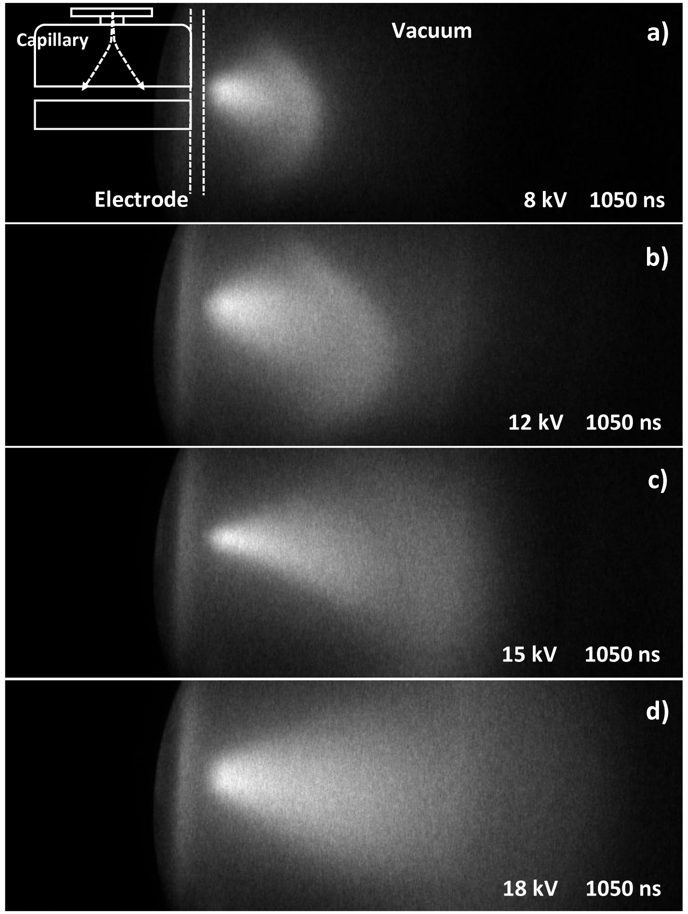


- plasma leakage
- plasma-bema dynamics ramps cannot be neglected

Works by: A. Biagioni (exp), E. Brentegani (sims)

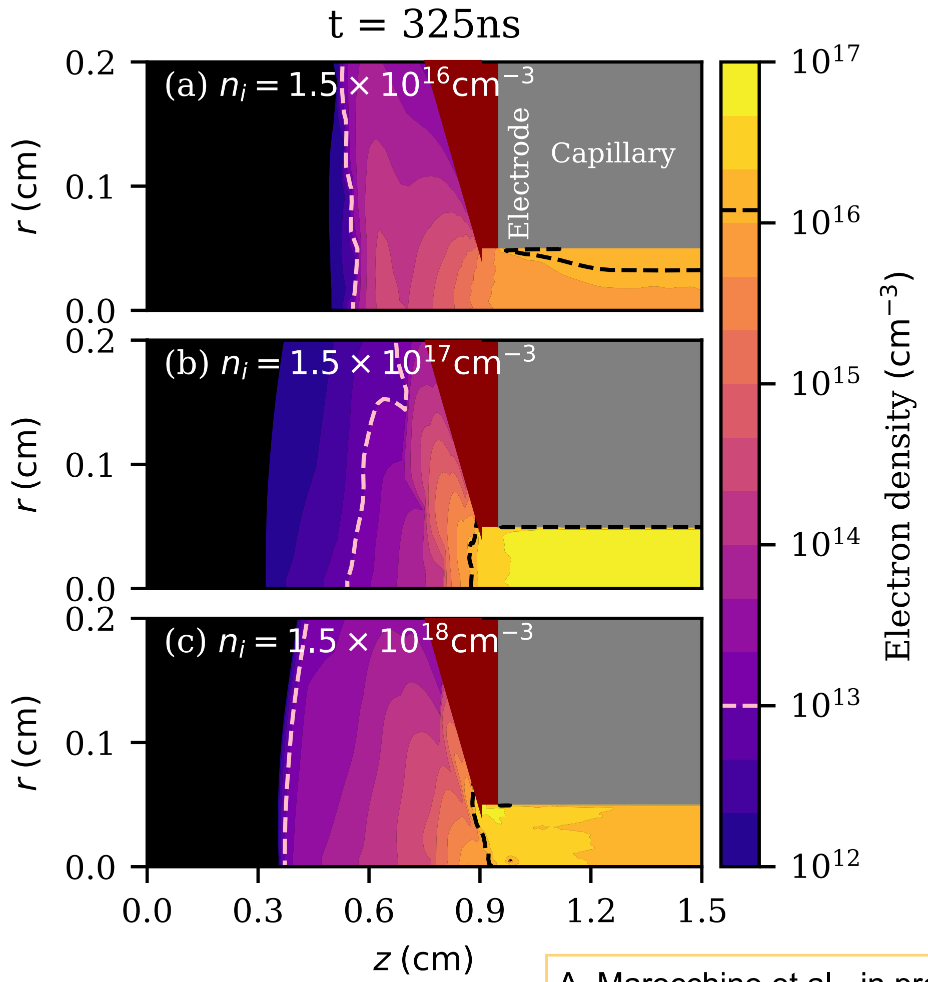
plasma acceleration capillary

experiments



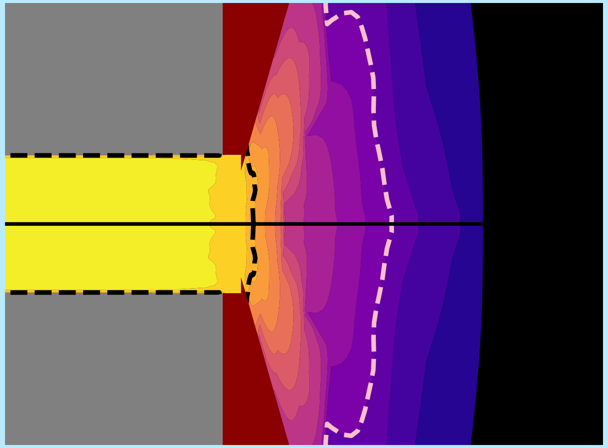
Stark broadening - interferometry

MHD simulations



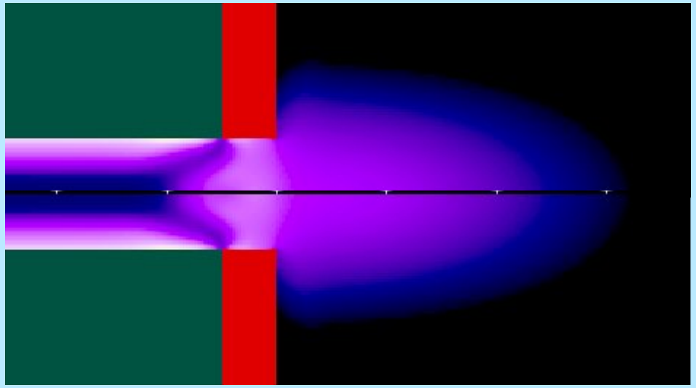
A. Marocchino et al. -in prep-

Hydro Code for Capillary Discharge



DUED

- Lagrangian code
- HEDP oriented :: *multi-physics*
- well established experience and know-how by the group

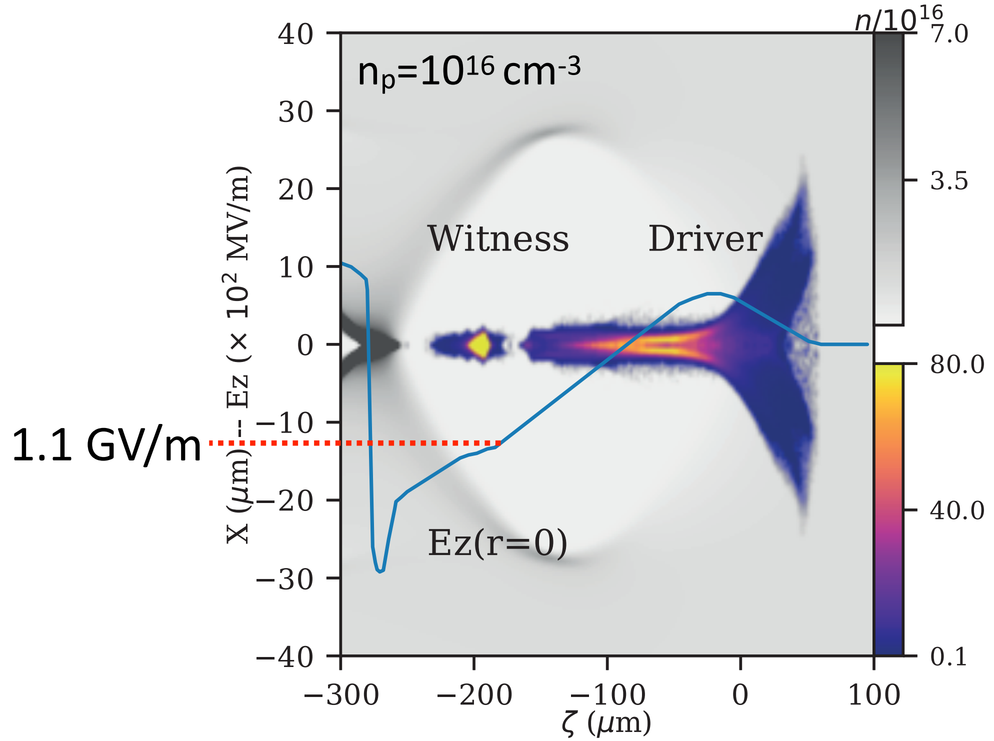


Pluto

- Eulerian code
- Astrophysical oriented
- We implemented: new heat conduction model, new magnetic diffusion model (semi-implicit)

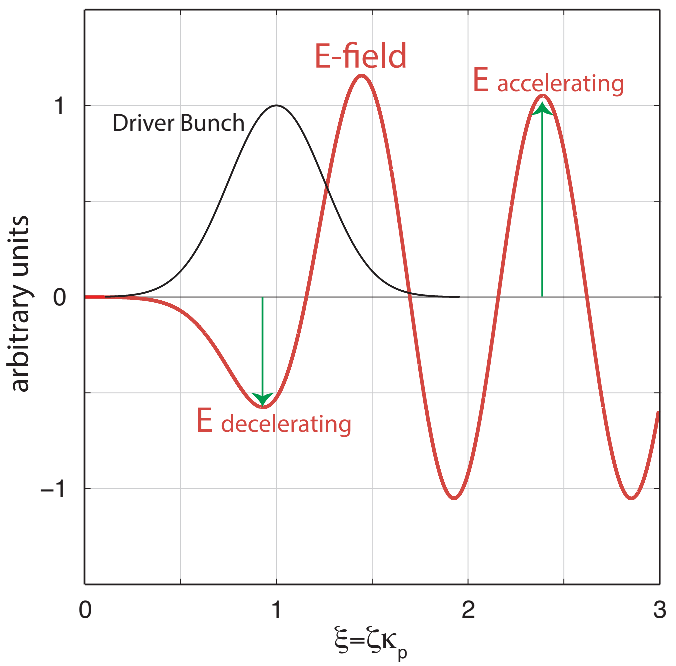
plasma acceleration

plasma acceleration



- flattening of the accelerating field
- the driver exhibits a expanded head profile

transformer ratio

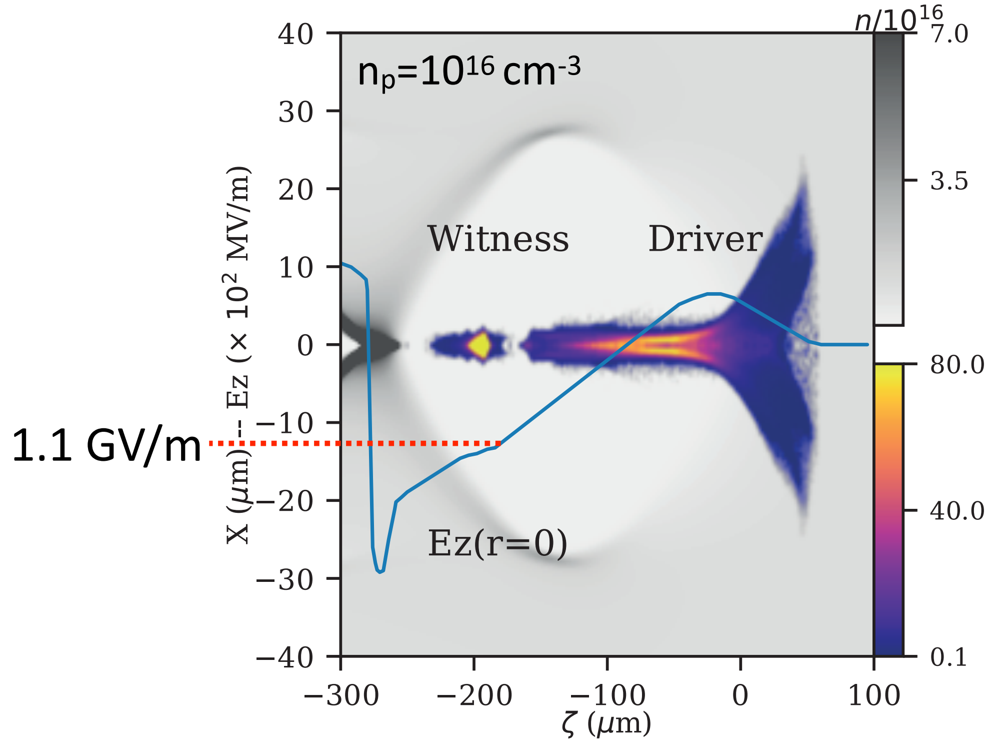


$$R = \frac{E_{\mathrm{acc}}}{E_{\mathrm{dec}}}$$

our case $R_{\mathrm{effective}}$~2.5

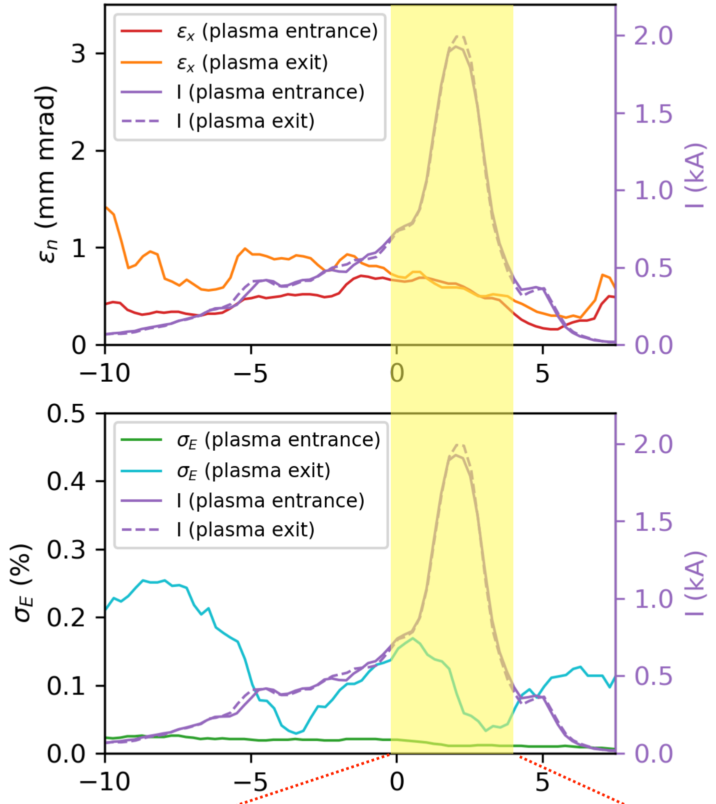
plasma acceleration

plasma acceleration



- flattening of the accelerating field
- the driver exhibits a expanded head profile

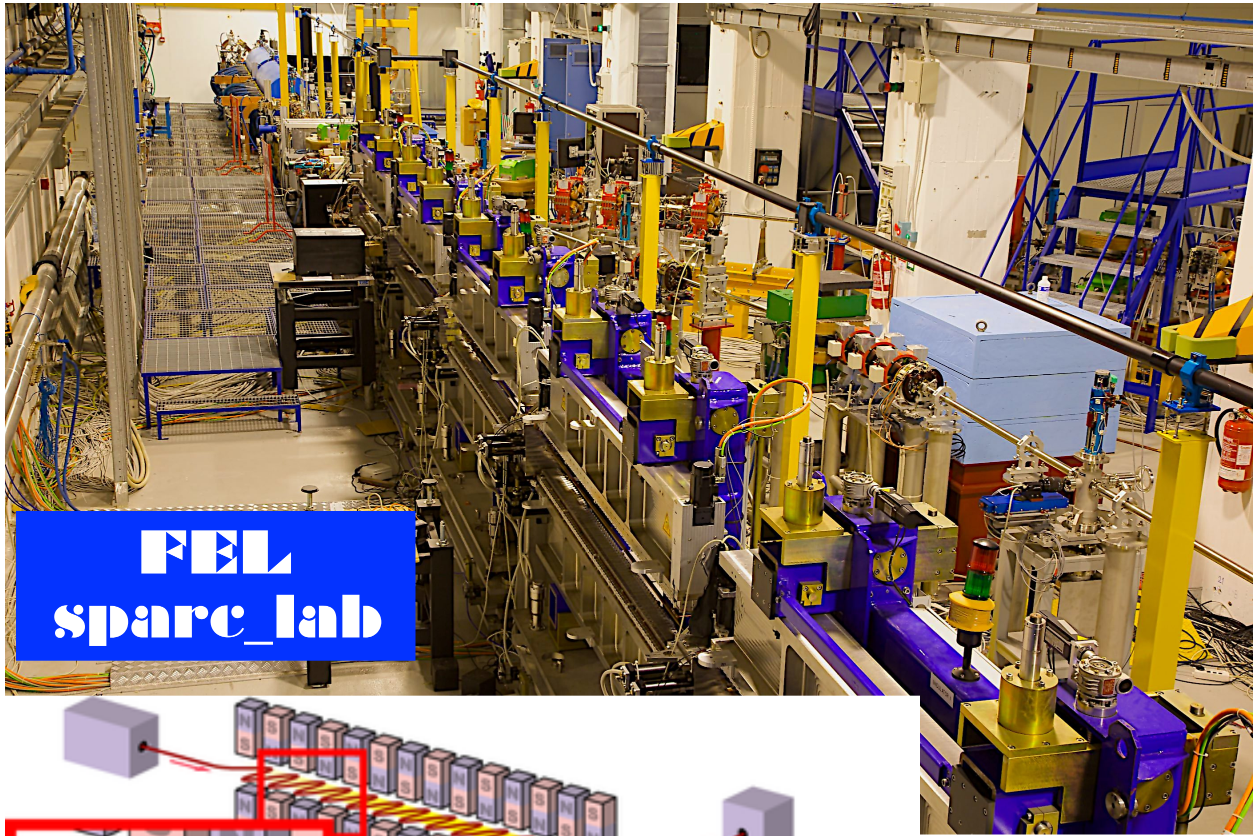
slice analysis

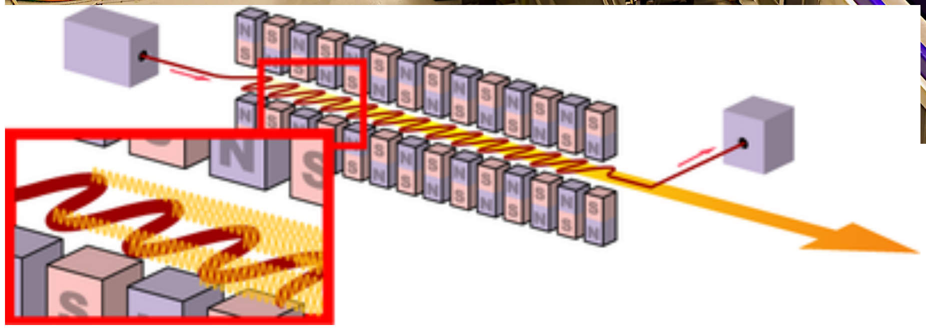


high sliced quality in the peak current region

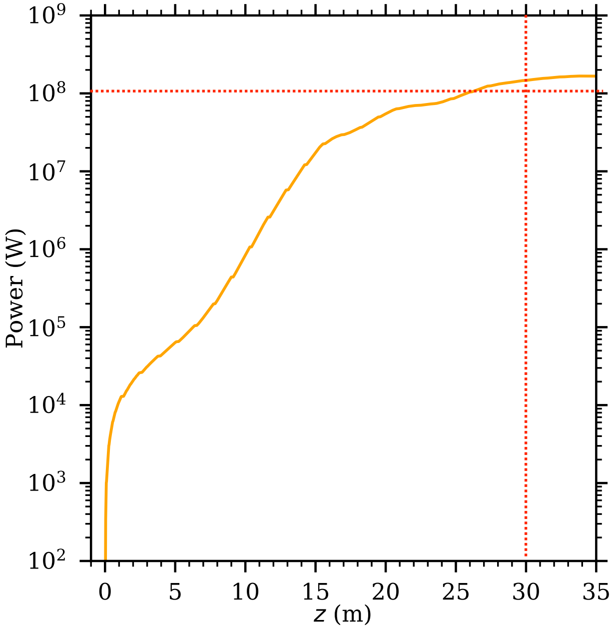
Free Electron Laser

SPARC_LAB FEL



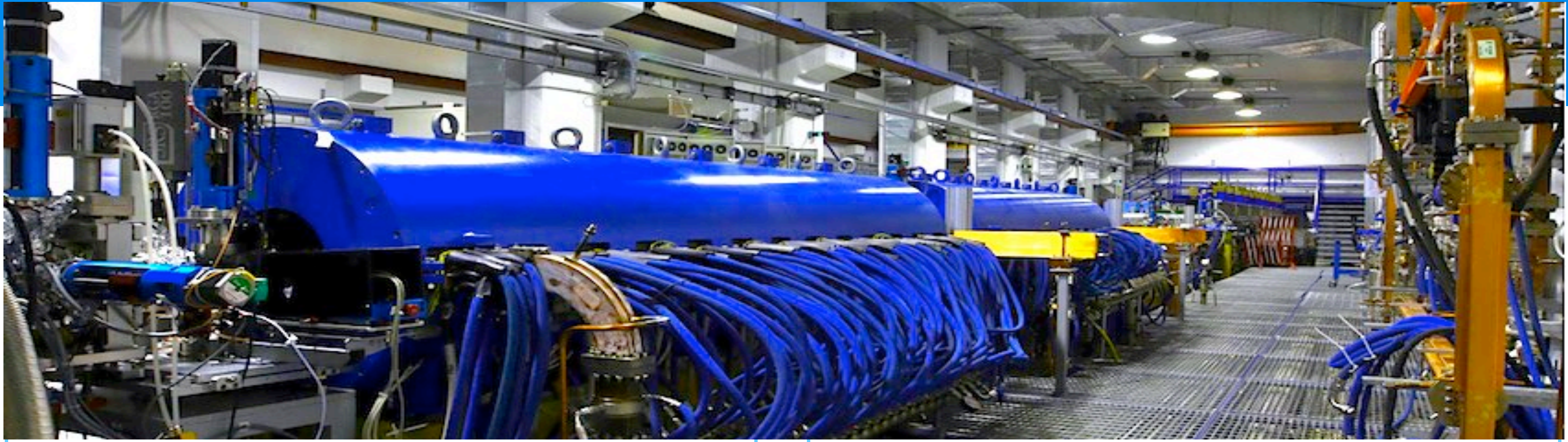


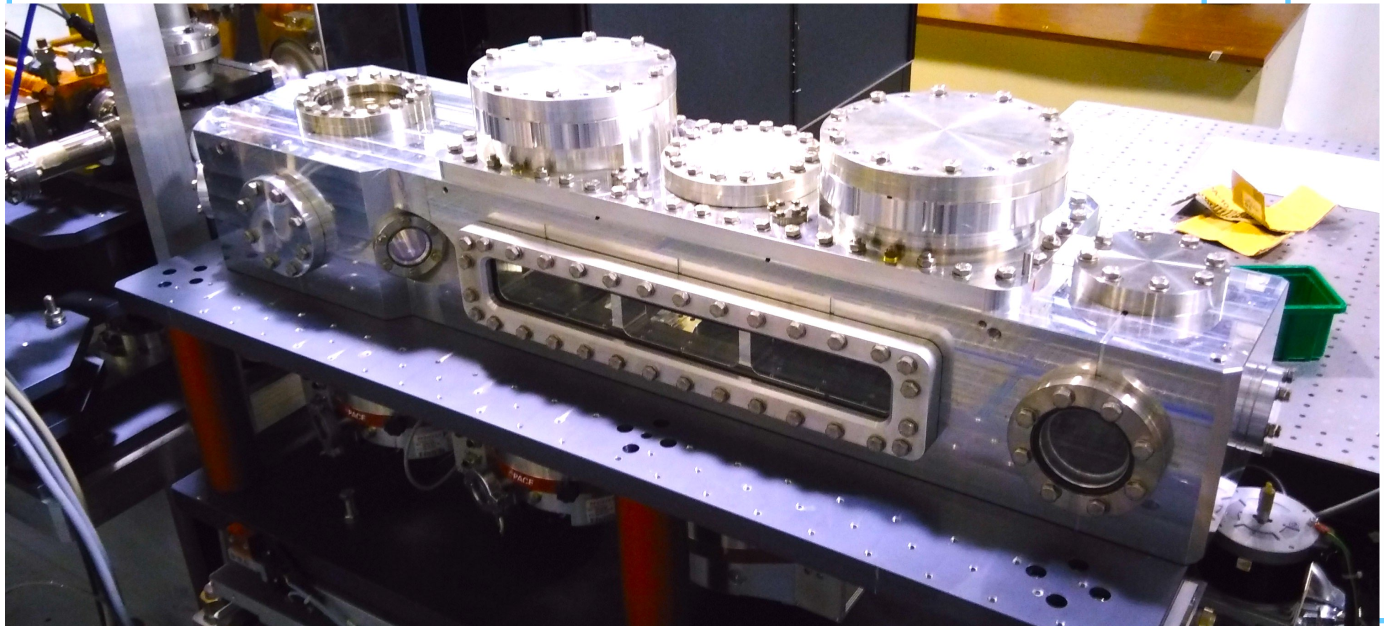
FEL performance



- a_w=0.8
- λ=3 nm
- saturation length 30 m
- 9.76 10^{10} photons per shot
- Power :: 10^8 Watt

A MAROCCHINO

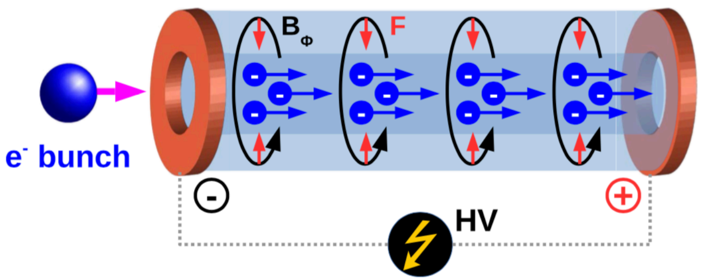


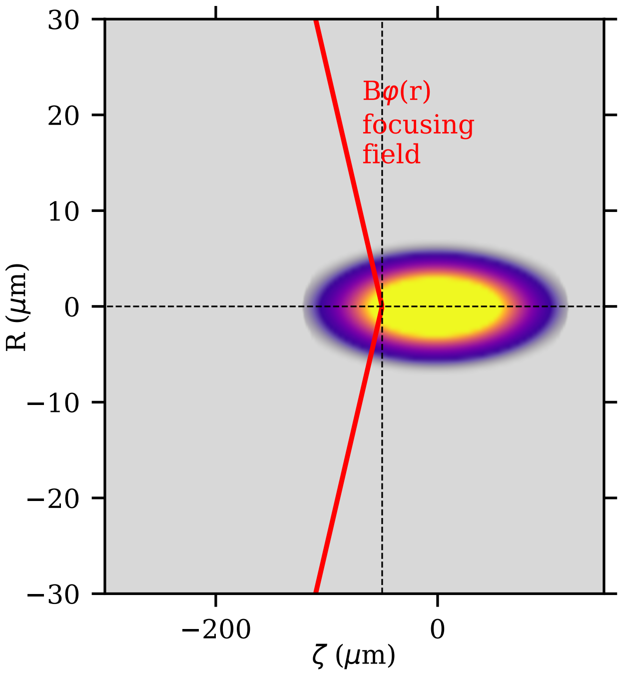


SPARC_LAB
Frascati
Italy

plasma lenses

active focusing mechanism

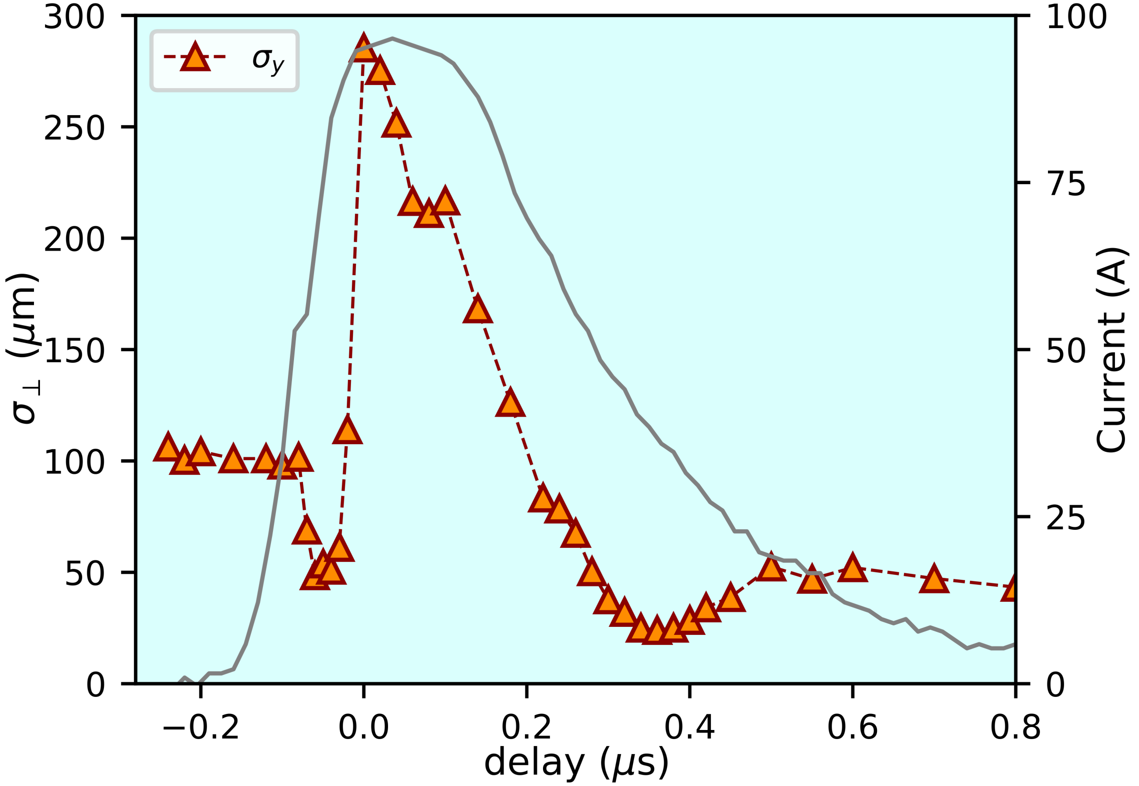




the motion of the background electron produces a **poloidal-focusing field**

experimental results

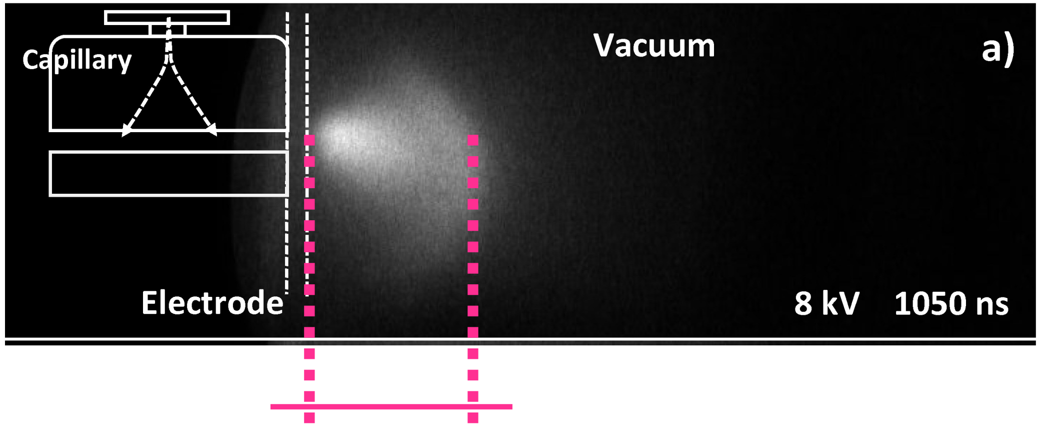
beam transverse dimension *on monitor*



A. Marocchino et al. APL (2017) DOI: 10.1063/1.4999010
R. Pompili - A. Marocchino et al. APL (2017) DOI: 10.1063/1.4977894
R. Pompili - A. Marocchino et al. PRL (2018) Accepted

plasma acceleration capillary

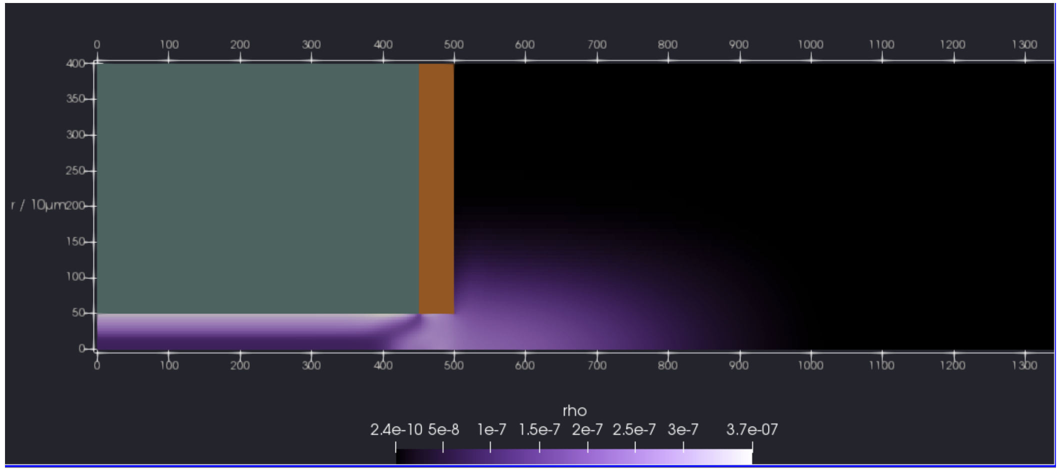
experiments



Necessity to control the plasma jet:

- limit the extension
- bunch focusing with no quality depletion

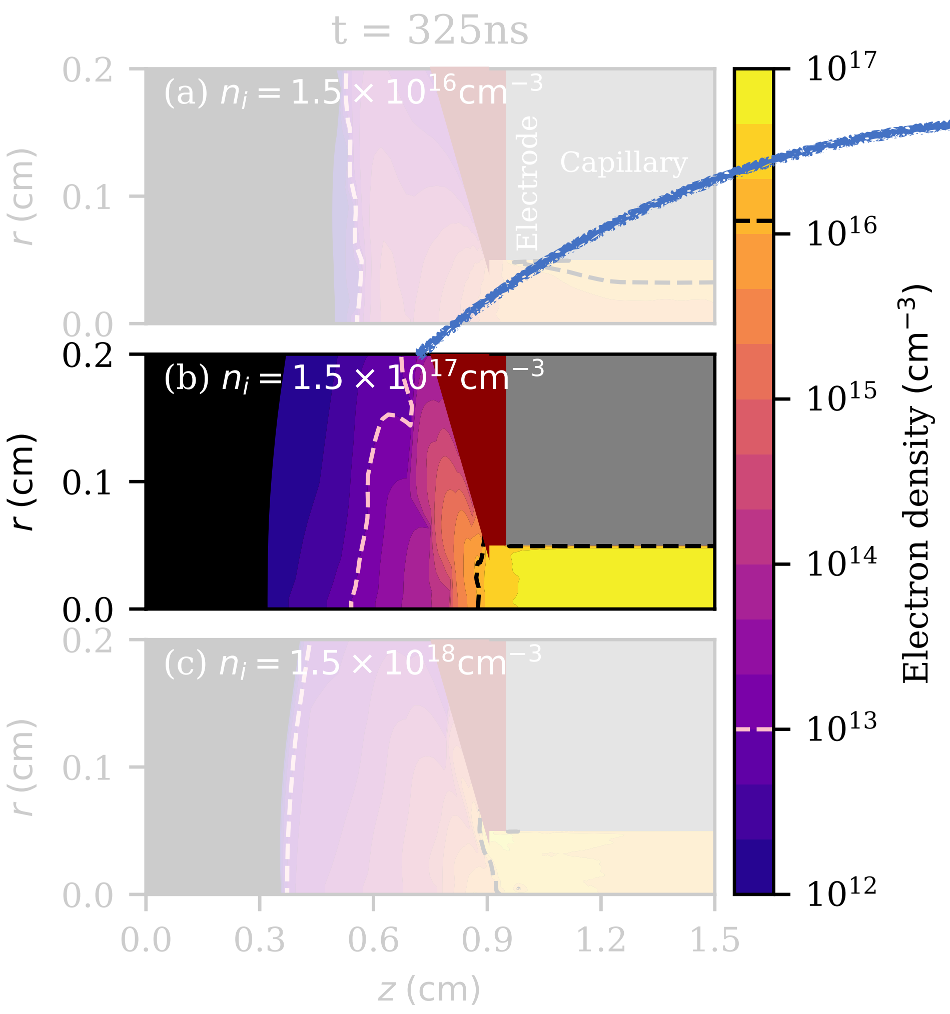
MHD simulations *(Pluto-Code)*



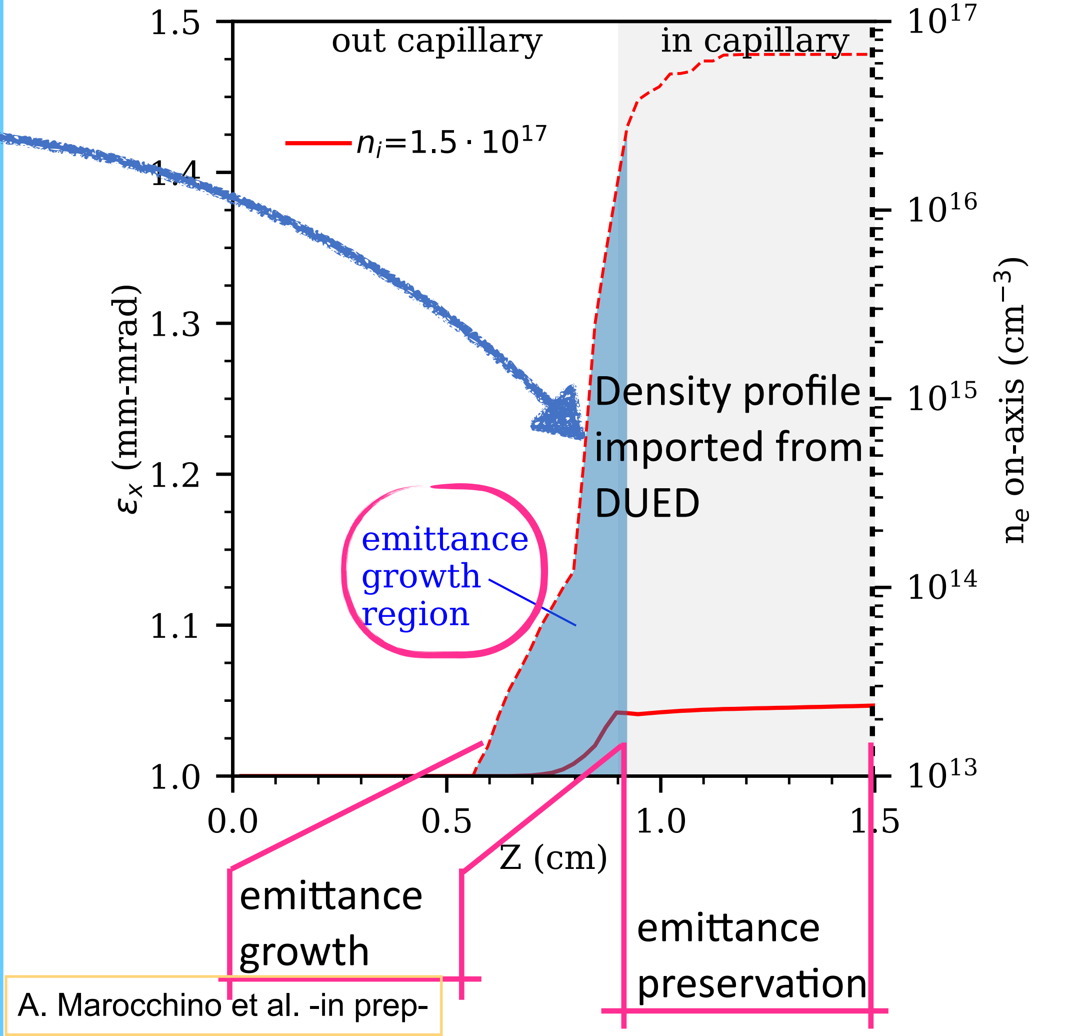
- MHD simulations to calculate a **realistic density profile**
- We use as **background density input in Architect**

emittance *ramp* growth

density profile *(DUED sims)*

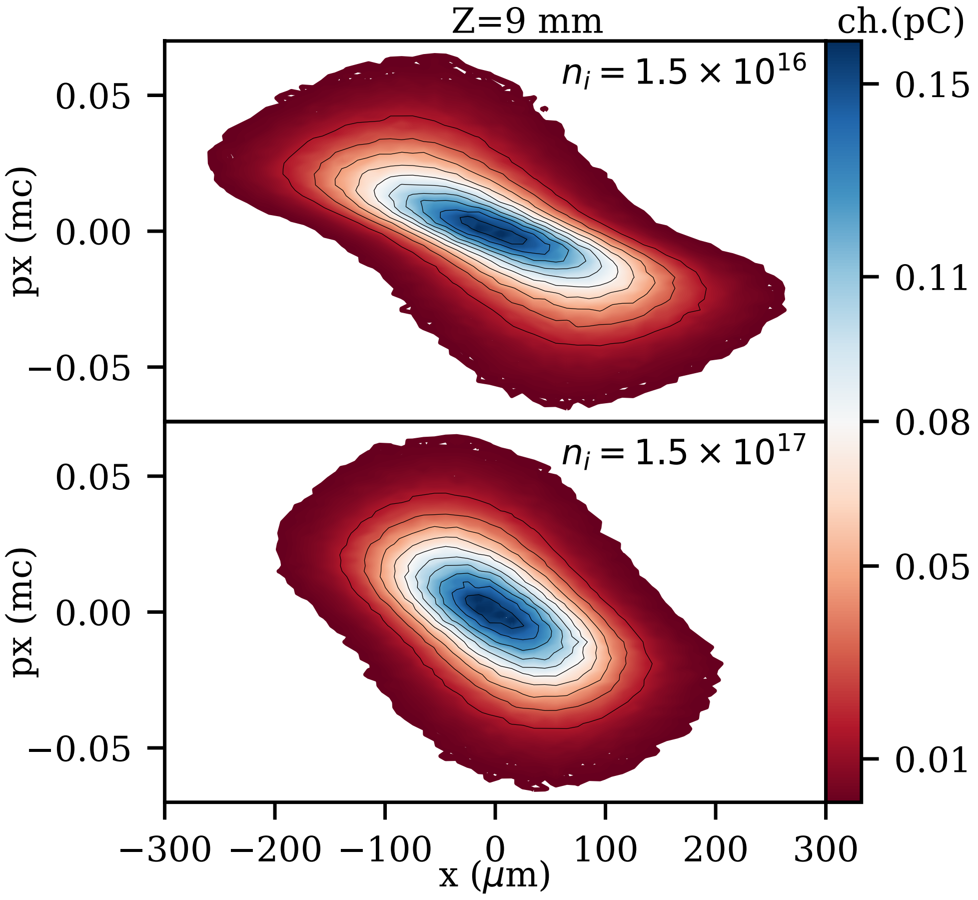


emittance growth: uncontrolled ramp

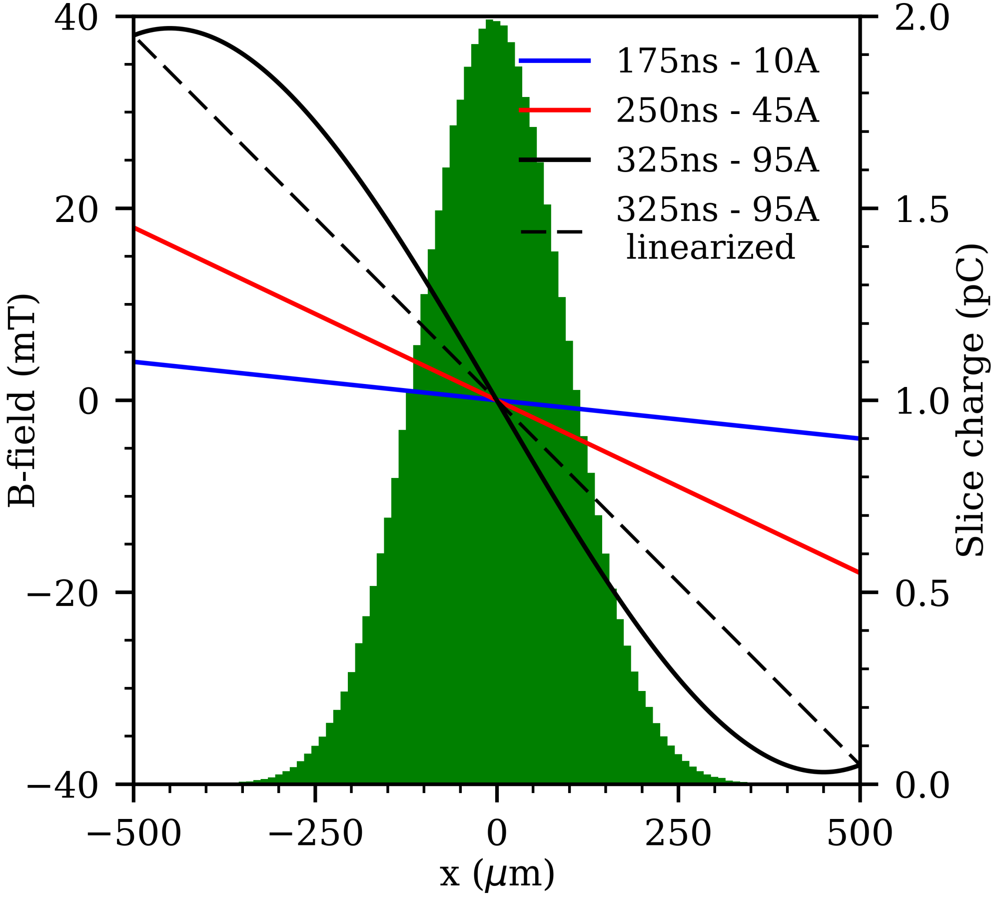


emittance growth

1) Density ramp Phase-Space rotation

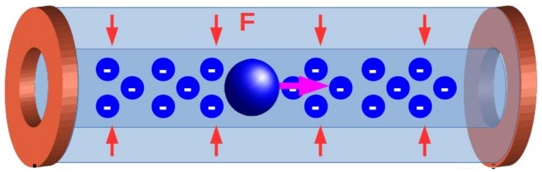


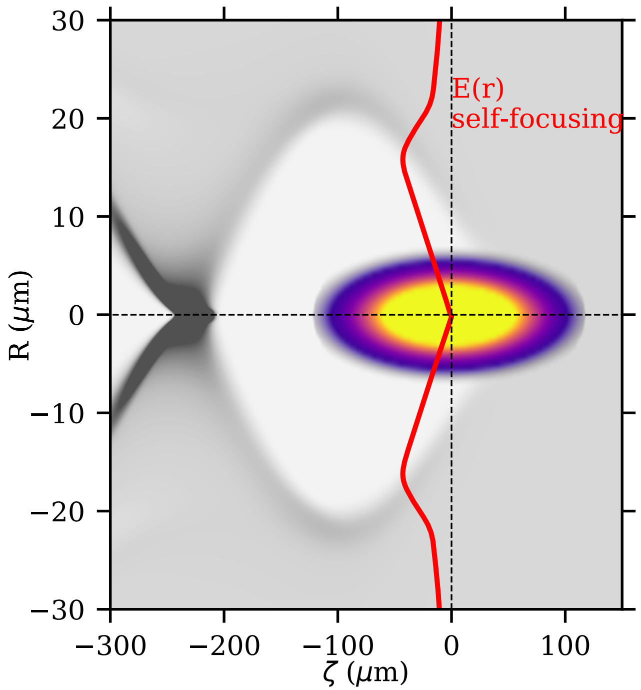
2) non-linear B-field :: aberration



plasma lenses

passive focusing mechanism





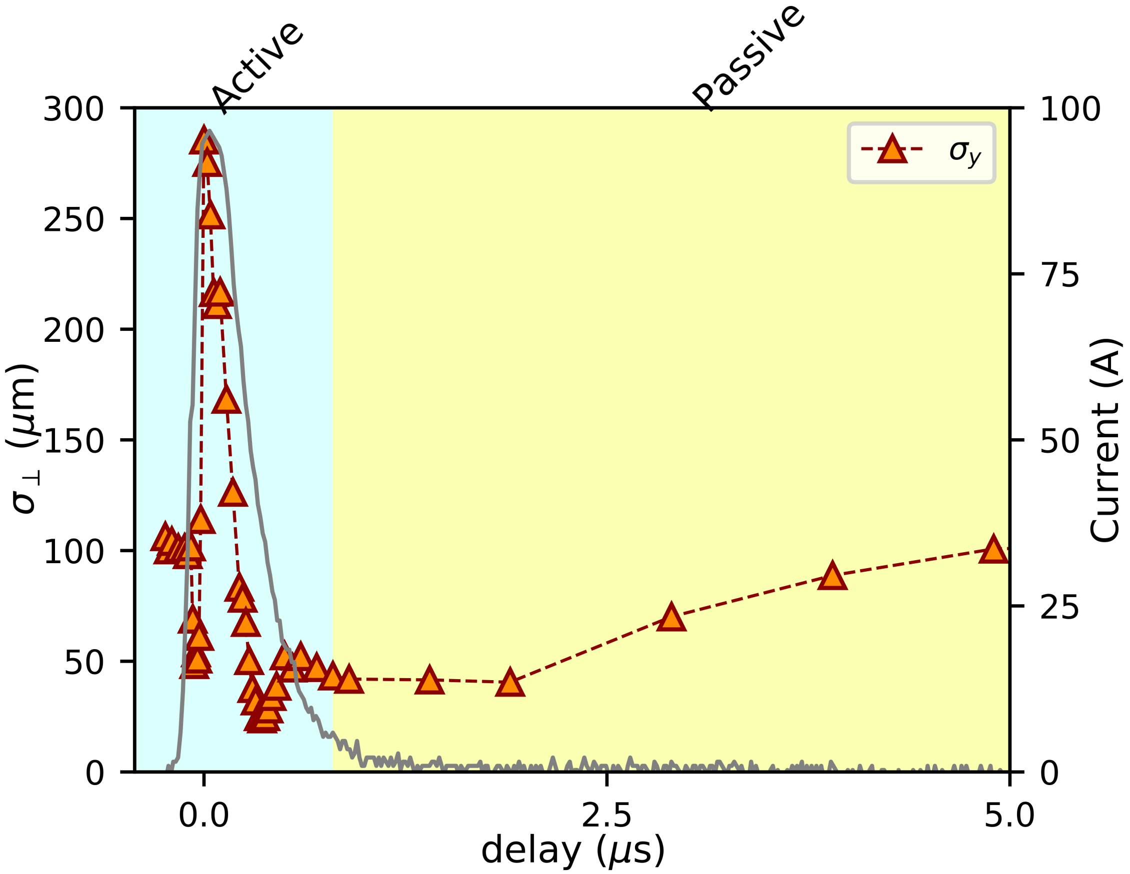
Transverse focusing

by

the bubble transverse field: **Er**

experimental results

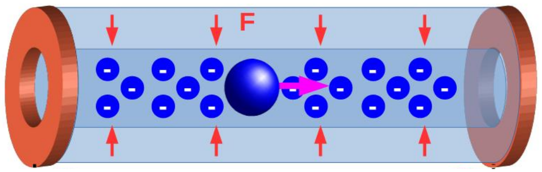
beam transverse dimension *on monitor*

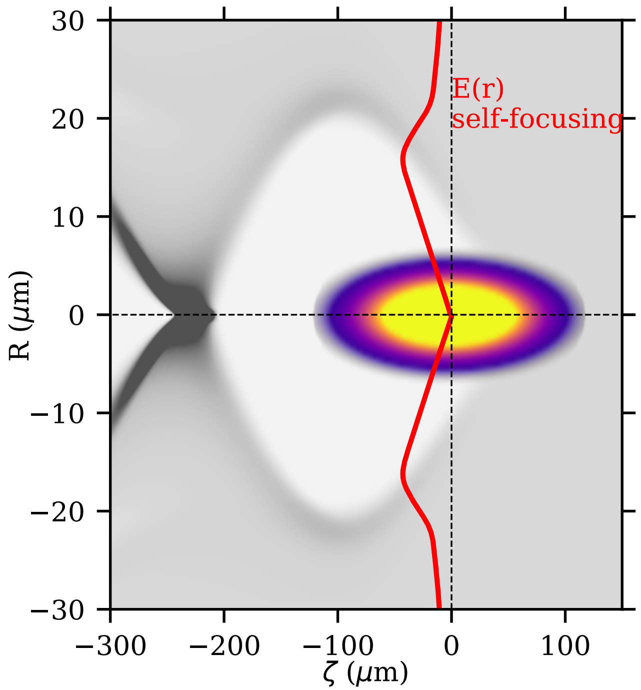


A. Marocchino et al. APL (2017) DOI: 10.1063/1.4999010
R. Pompili - A. Marocchino et al. APL (2017) DOI: 10.1063/1.4977894

plasma lenses

passive focusing mechanism



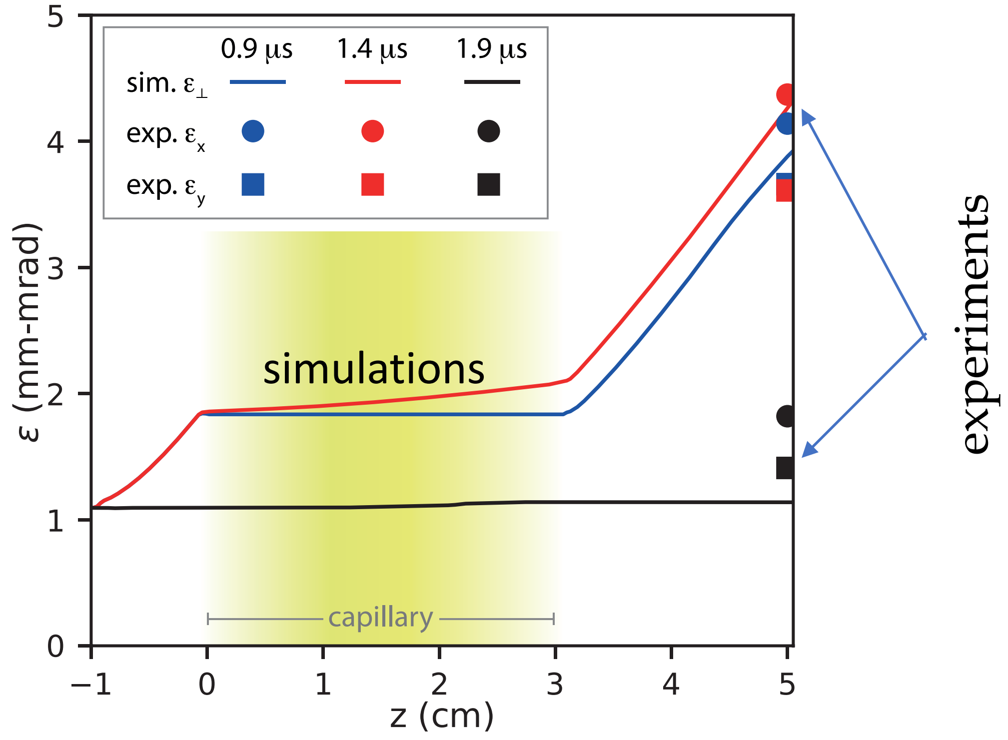


Transverse focusing

by

the bubble transverse field: **Er**

Experiments VS simulations

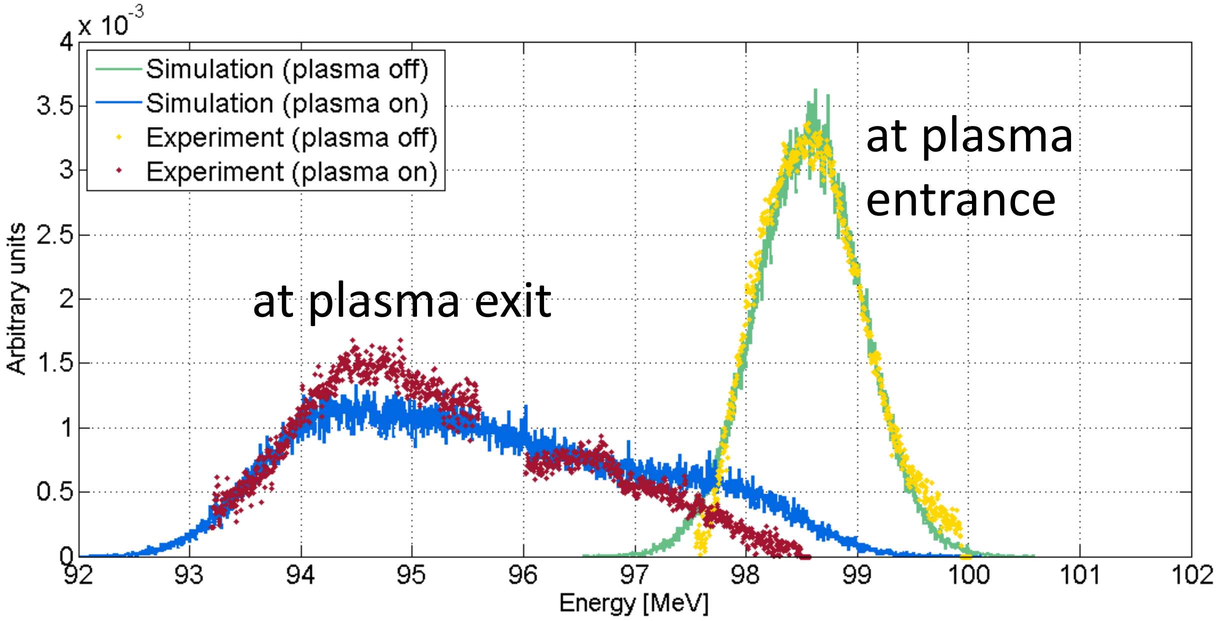


quality degradation for long bunches and densities higher than bunch density

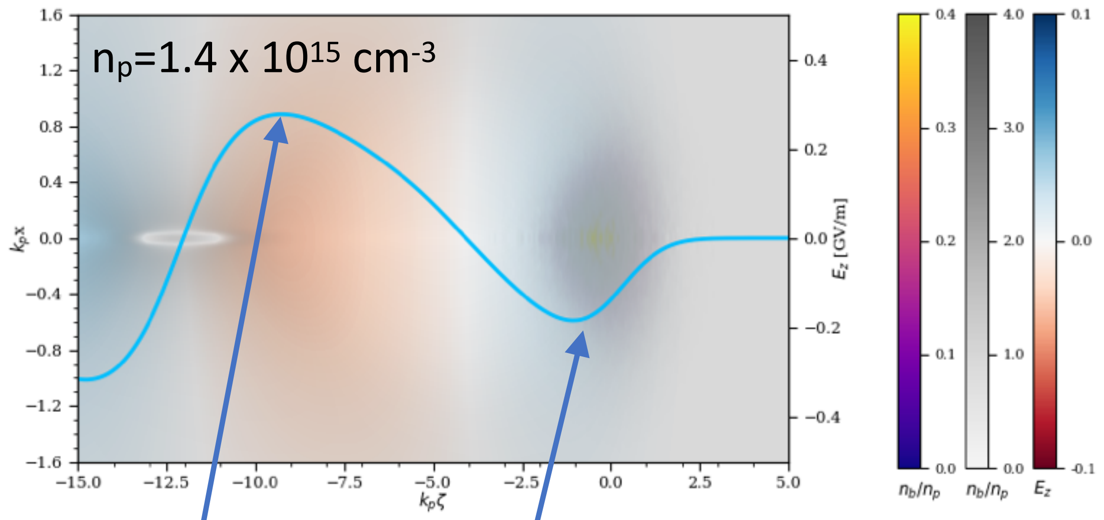
A. Marocchino et al. APL (2017) DOI: 10.1063/1.4999010

deceleration experiments

plasma deceleration - code benchmarking



max E-field

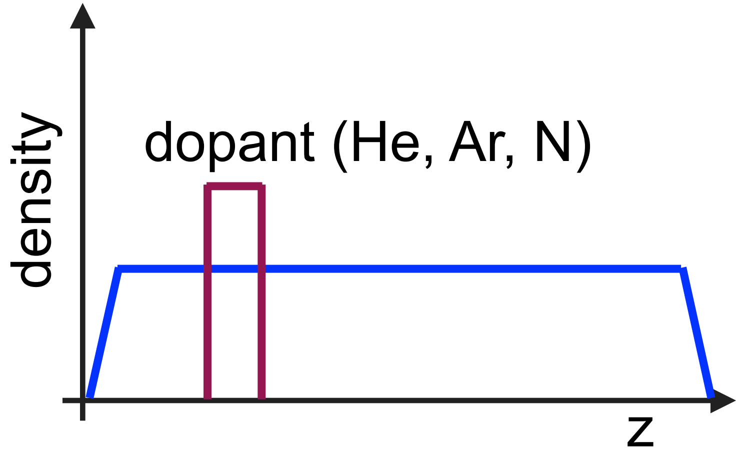


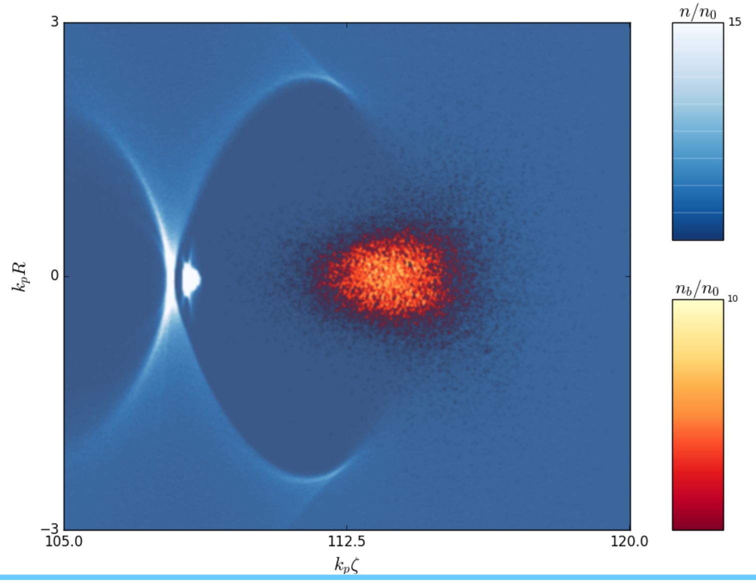
$Ez_{accelerating}$ >300 MV/m

Ez=200 MV/m

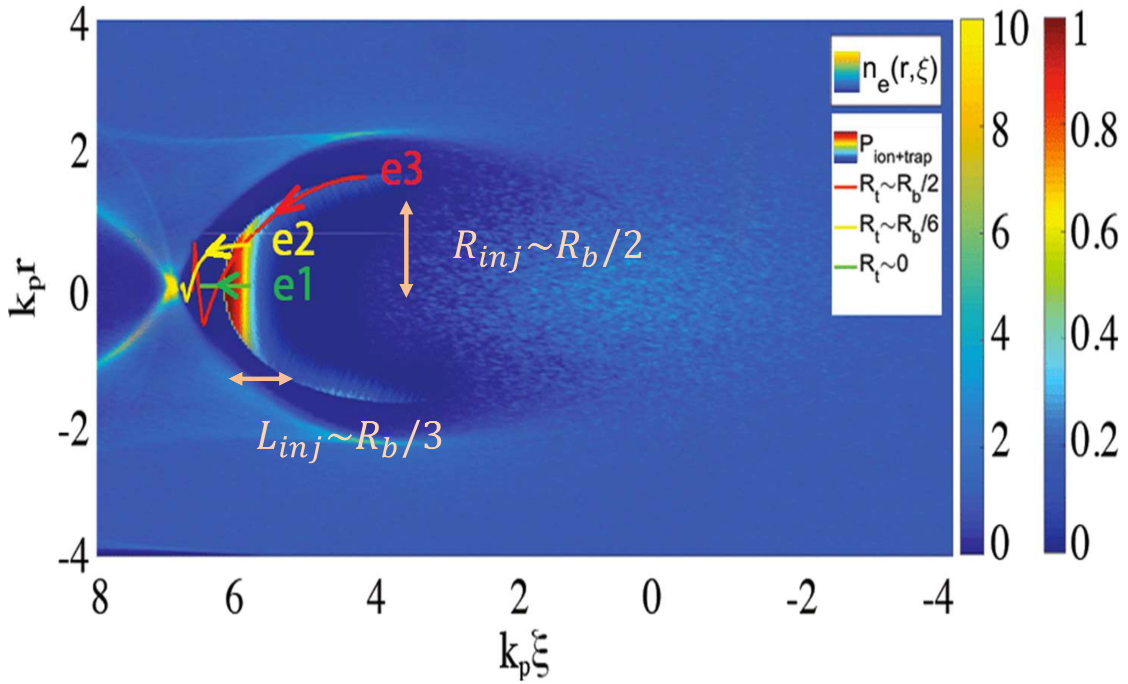
ionisation injection

setup





max E-field



- Injection position (Extraction) is a key parameter to control the beam quality
- off-axis particle cause of emittance growth

F. Mira - A. Marocchino et al. NIM-A 2018, DOI: 10.1016/j.nima.2018.01.019

CONCLUSIONS

- A realistic simulation from the Photo-injector to the FEL for the future EuPRAXIA@Sparc_Lab facility
- 1.1 GV/m + quality preservation + FEL seeding
- EuPRAXIA@SPARC_LAB an ongoing project!
- New results at SPARC_LAB from Plasma lenses to Plasma deceleration