EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Simulations and Performance

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EAAC 2017, Sept. 19th

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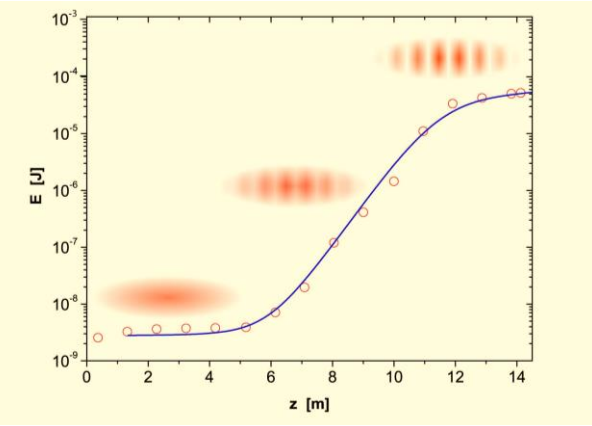
Electron beam requirements

Horizon 2020

- Among the various applications considered in EuPRAXIA, the hardest e-beam requirements likely come from FEL

Quantity	Symbol	Baseline value
Particle type	e	Electrons
Energy	E	5 GeV
Charge	Q	30 pC
Bunch length (FWHM)	τ	10 fs
Peak current	I	3 kA
Repetition rate	f	10 Hz
Number of bunches	N	1
Total energy spread (RMS)	σ_E/E	1%
Slice energy spread (RMS)	$\sigma_{E,S}/E$	0.1 %
Trans. Norm. emittance	$\varepsilon_{N,x}$, $\varepsilon_{N,y}$	1 mm mrad
Alpha function	α_x, α_y	0
Beta function	β_x, β_y	5 m

Target values for the 5 GeV electron beam parameters at the entrance of the undulators (IPAC EuPRAXIA paper)
Table also valid for the 1 GeV e-beam, though
1.5 kA peak current with smaller ε & σ_E is also considered



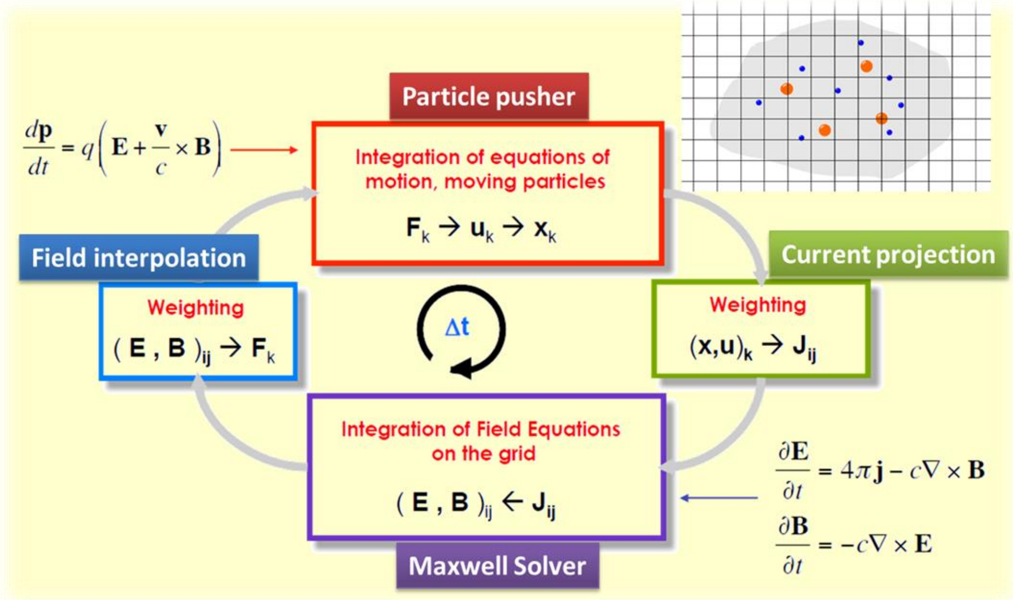
Critical parameters

$$\frac{\sigma_\gamma}{\gamma} << \rho \qquad \frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{2\pi}$$

- ✓ high peak current
- ✓ very low emittance
- ✓ very small energy spread

Numerical simulation tools

- Electron acceleration in plasma cannot be fully predicted by analytic theory owing to nonlinear effects of laser pulse evolution, wakefield evolution and motion of the accelerated beam
- Particle-In-Cell (PIC) codes widely used tool for the investigation of both laser- and beam-driven plasma acceleration



- Inluding sophisticated techniques, as: Moving window (mandatory for long propagation lengths) Parallelization (mandatory for 2D-3D simulations) Flexible and quick output analysis, Ionisation (Field Ionisation / Collision Ionisation) etc
- With all variants to speed up simulations: Lorentz boosted frame, azimuthal Fourier decomposition, hybrid kinetic-fluid codes, etc
- And dispersion-free algorithms to mitigate numerical Cherenkov instability : FDTD (finite-difference time domain, as Yee scheme) vs PSATD (pseudo-spectral analytical time domain) algorithms

Simulation codes

Simulation codes used in EuPRAXIA-WP2 for laser-driven plasma acceleration, as well in WP9 and WP14 for beam-driven plasma acceleration

PIC code used	Users	additional features
OSIRIS	IST, DESY	Boosted frame technique, quasi-3D cylindrical field harmonics, PGC* algorithm in 3D (laser envelope)
WARP	CNRS/LPGP, CEA	Boosted frame technique, quasi-3D cylindrical field harmonics, adaptive mesh refinement
CALDER-Circ	LOA	Quasi-3D Cylindrical field harmonics
SMILEI	CNRS/LLR	Dynamic load balancing
ALaDyn Architect	INFN_SparcLab (PISA_ILIL)	full PIC code, bunch & bg treated with macroparticles hybrid code, bunch as PIC and bg as fluid (no QSA)
HiPACE	DESY	Full 3D PIC code, Quasi-static approximation (PWFA)
PIConGPU	DESY	designed to run on Graphical Processing Units (GPUs)

* Ponderomotive Guiding Center

Stability study with PIC codes

Horizon 2020

- **Typical table of errors:**
  misalignment, fluctuation of plasma density, injected e-beam and laser pulse

		Min. Value (ex. jitter)	Max. Value (ex. slow drifts)
plasma			
	density	1%	10%
alignment error (plasma axis wrt e-beam and laser)			
	position [µm]	1	5
	angle [µrad]	1	10
e-beam and driver synchronization			
	Time shift [fs]	1	10
plasma lens			
	Magnetic field	1%	10%
Injected e-beam			
	charge	10%	20%
	energy	10%	20%
	emittance	10%	50%
	bunch length	10%	20%
Laser (global fluctuations)			
	Energy	5%	20%
	beam spot radius	10%	20%
	intensity	10%	20%
	focal plane position [mm]	0.1	1
	Pointing stability	1 µrad	1 µrad

+ laser pulse imperfections

most published simulations use perfect Gaussian profiles

Transverse profile

Super-Gaussian $I(\rho)=I_0\exp\left[-(\rho/w)^\alpha\right]$

α=2 Gaussian profile
α=4-10 "top-hat" profile

with angular asymmetries

$$A_L(\rho,\theta)=\sum_m A_m(\rho,\theta)\exp[-im\theta]$$

mode decomposition m=1,2

Time profile of the laser pulse

$$A_L(z,\rho,\theta,t)=A_L^0(z,\rho,\theta)\exp\left[-(\tau/\tau_L)^2-i(\omega\tau+\varphi_L)\right]$$

φ_L relative phase between high-frequency laserfield and envelope

Spatio-temporal correlation

$$\varphi_L(\omega,\vec{\rho})=\varphi_L(\omega_0,\vec{\rho})-\delta\varphi_L$$

$\delta\varphi_L$ phase variation of spatial-temporal correlation

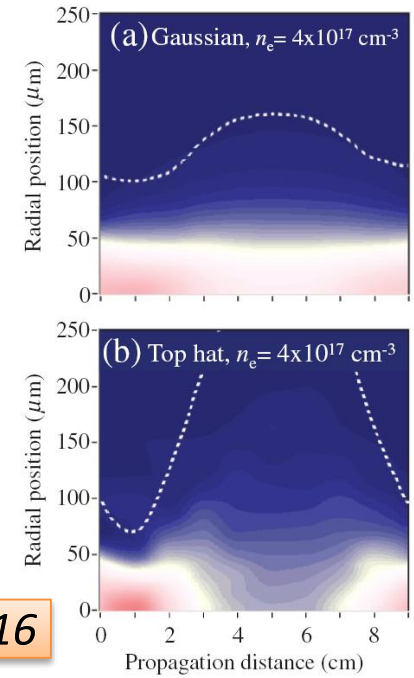
can be inferred from new experimental technics enabling the measurement of such correlations
G. Pariente et al, Nature Photonics 10, 547 (2016)

Gaussian/realistic laser pulses

❑ Transverse intensity profile of laser pulse

- LBNL experiment capillary discharge waveguide
  - the fluence profile evolution of the laser pulse through the waveguide depends strongly on the initial profile Gaussian or top-hat (large diffraction in the middle)

W.P. Leemans et al PRL 113, 245002 (2014)

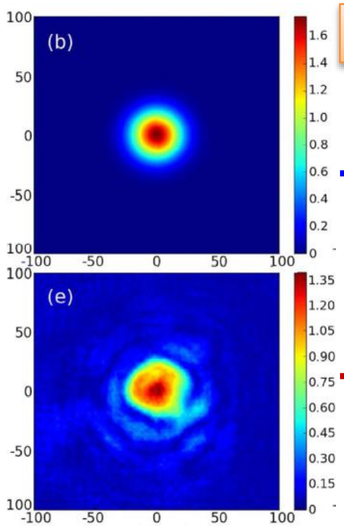


❑ Transverse intensity distribution and wavefront distortion

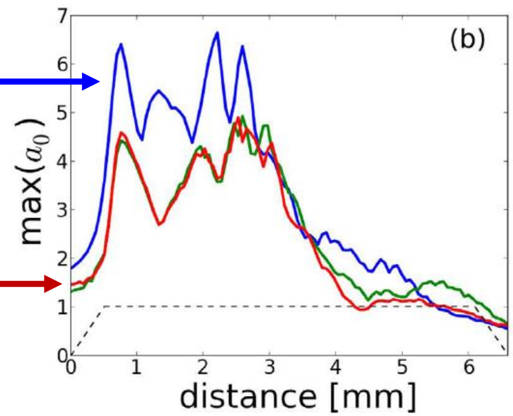
J. Ferri et al, Nature Scientific Report, June 2016

Gaussian

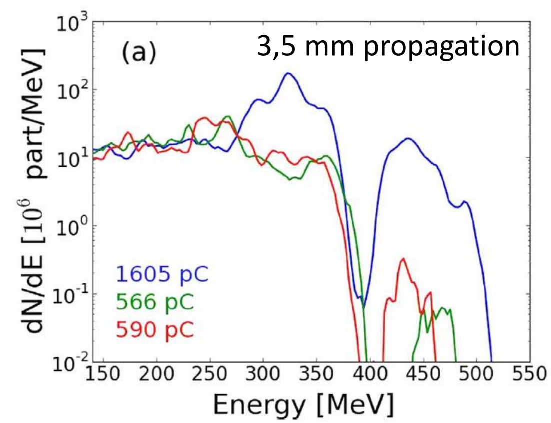
Exp. Spot and phase



Initial laser spot



potential vector evolution

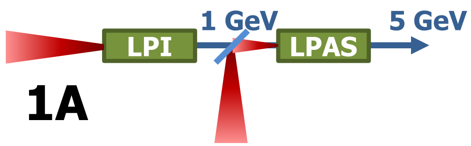


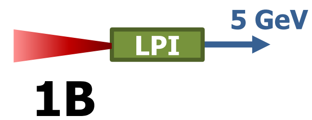
Energy spectrum of e-

Laser driven / Beam driven PA Configurations

Horizon 2020

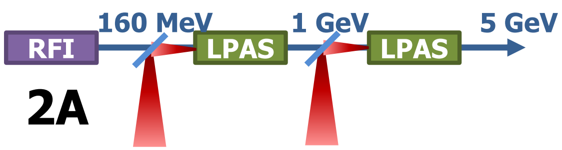
- **Config 1: LPA with internal injection**

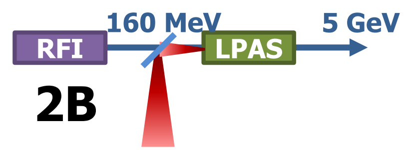




High-energy LP Injector

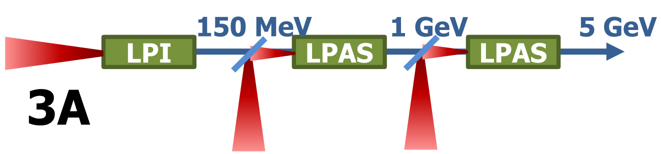
- **Config 2: LPA with external injection from RF injector**

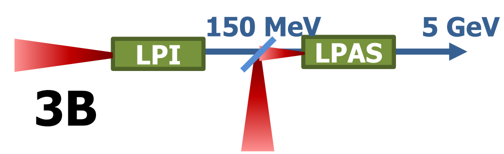




Low-energy RF Injector

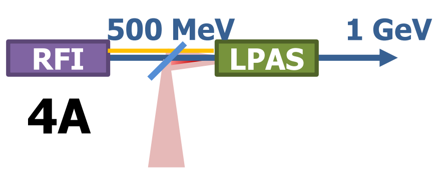
- **Config 3: LPA with external injection from Laser Plasma injector**

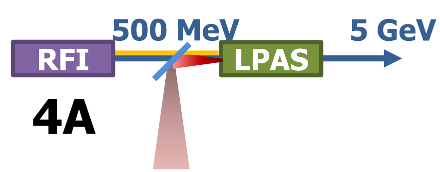




Low-energy LP Injector

- **Config 4 : BPA with external injection from RF injector**



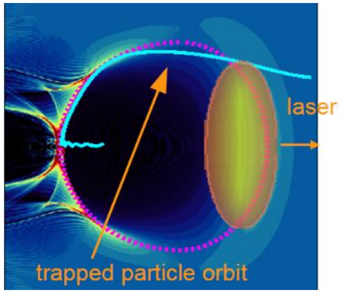


High-energy RF Injector

Problematics

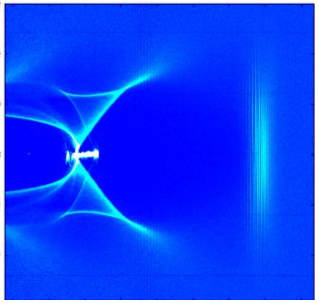
- High-energy LP injector
  - Can we inject (self-injection) and accelerate a beam with good quality (meeting user requirements) to 1, 2, …5 GeV in a single stage ?
- Low-energy LP injector
  - What is the most promising method to achieve a 150 MeV beam with good quality to be further accelerated (meeting the FEL requirements) ?
- RF injector
  - Inject the beam with expected parameters from RF photo-injector high energy / low charge ?
- Plasma accelerating section
  - What are the most promising options ?
    Non-linear with self-guiding / linear regime with plasma channel

- **Problematic 1**
  Can we inject (self-injection) and accelerate a beam with sufficient good quality
  (meeting user requirement)
  to 1, 2, …5 GeV in a single stage ?



Self-injection

High-energy LP Injector



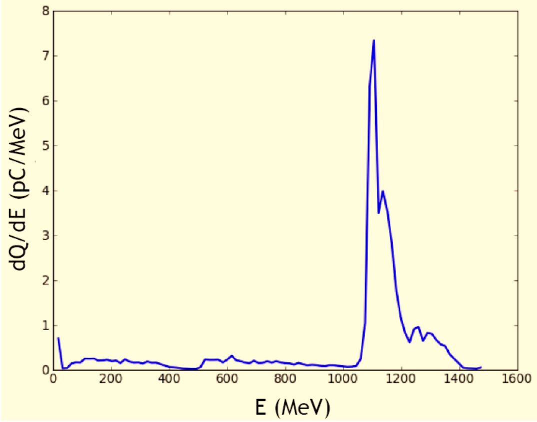
- Based on **self-injection method**

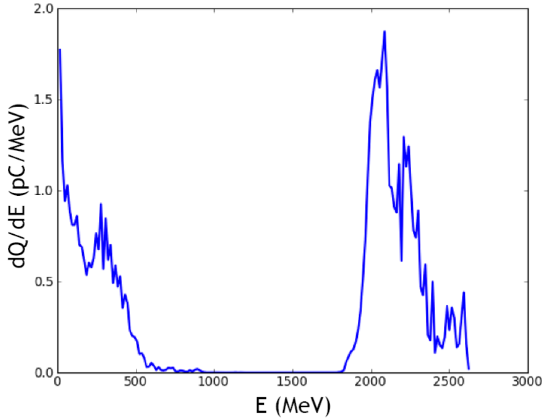
1. relativistic self-focusing of the pulse to create the ponderomotive blowout
2. transient bubble expansion sufficient to trigger self-injection of background electrons
3. rapid termination of self-injection and formation of a quasi mono-energetic bunch
4. acceleration to GeV energy over ~1 cm distance, without low-energy background

➢ 1 GeV LPI with 0.6 PW laser power [F. Massimo, A. Beck]

Laser		
Power	600 TW (15 J)	
Waist w_0	30 µm	
a_0	4.3	
Plasma		
Density n_0	8.6×10^{17} cm^{-3}	
Extracted beam		
	@0.7cm	@1.3cm
Energy	1.1 GeV	2.2 GeV
Charge	610 pC	530 pC
E spread rms	6.6 %	7.5 %
$\varepsilon_{N\,x,y}$ (mm.mrad)	1.5, 1.5	1.5, 1.7

Parameters from A. Beck, NIM A 740 (2014)
Simulations Calder-Circ with anti-Cherenkov stencil
R. Lehe, "Numerical growth of emittance in simulations of laser-wakefield acceleration", PRSTAB 16, 021301 (2013)

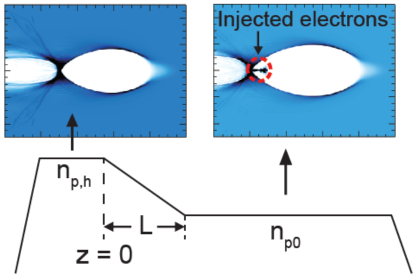


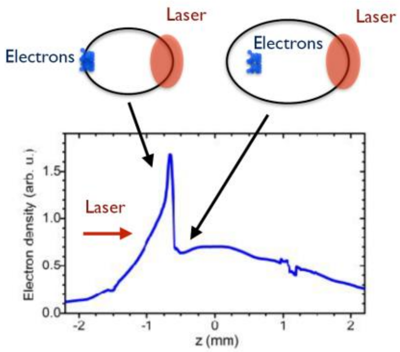


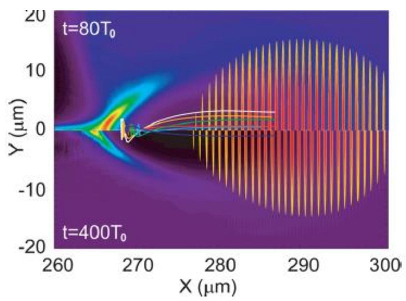
Suitable for FEL amplification ?

Low-energy LP Injector

- **Problematic 2 :**
  What is the most promising method to achieve a 150 MeV beam with good quality to be further accelerated in a LP section (meeting the FEL requirements) ?







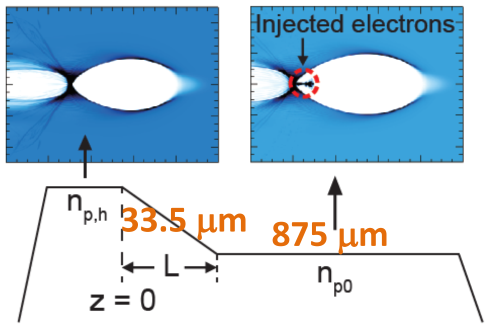
Soft density down-ramp | **Shock injection** | **Ionization injection** | **Other methods**

Low-energy LP Injector

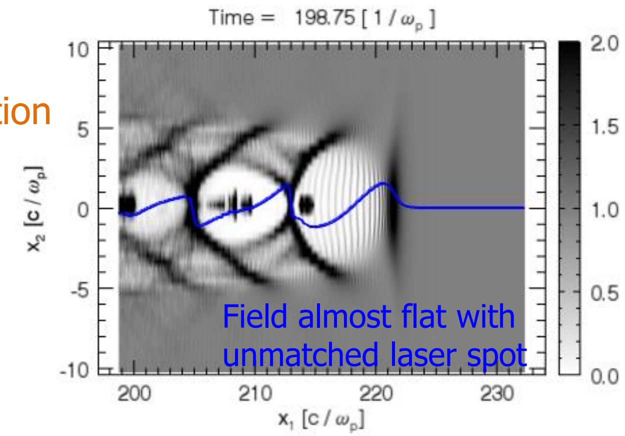
- Based on **down-ramp method** → *slows down the plasma wave*

n_{ph} = 1.5 x 10^{19} cm^{-3}

n_{p0} = 1.0 x 10^{19} cm^{-3}



OSIRIS Simulations with PGC approximation

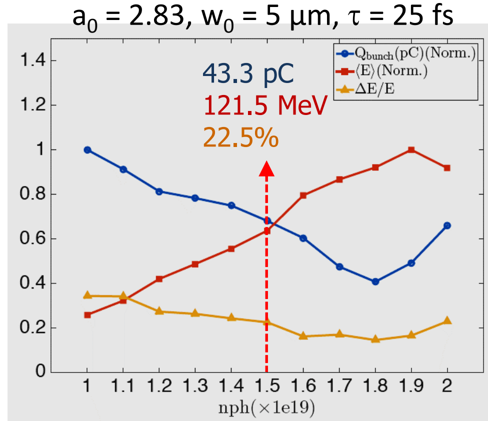


➢ 236 MeV 80pC [IST, U. Sinha, J. Vieira]

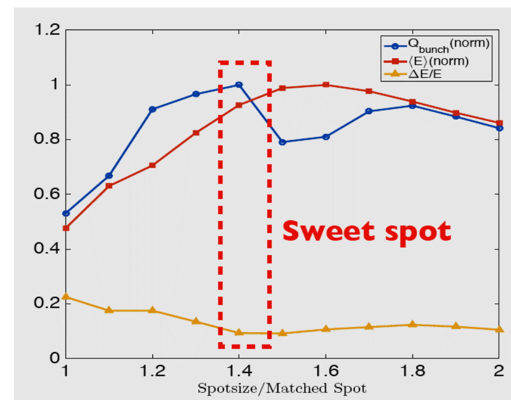
Laser	
Power	8.4 TW
Waist w_0	7 μm ~ 1.4 x matched spotsize
a_0	2.83
Plasma	
Density n_{p0}	1 x 10^{19} cm^{-3}
Extracted beam @sweet spot	
Energy	236 MeV
Charge	81.5 pC
E spread FWHM	9.3 %

@matched spot size

a_0 = 2.83, w_0 = 5 μm, τ = 25 fs



Density scan
constant density slope

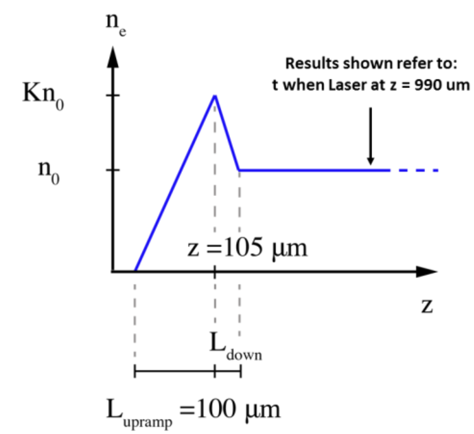


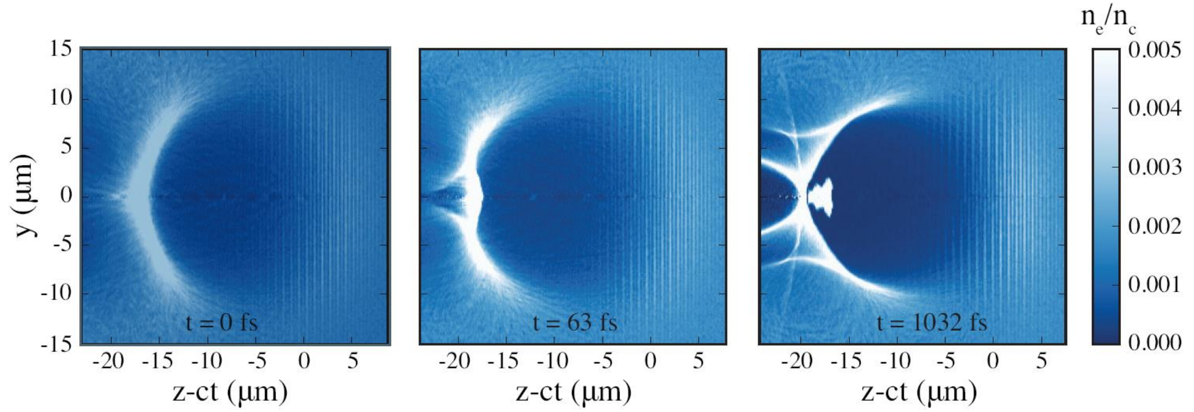
Laser spot size scan
5 → 10 μm

Low-energy LP Injector

- Based on **shock injection**
  - Changing length & height of the downramp
  - Scan parameters (for $a_0 = 2.5$)
    $L_{downramp}$ = 10 – 50 μm , K = 1.2, 1.3, 1.5

➢ 150 MeV 30 pC [LOA, F. Massimo]



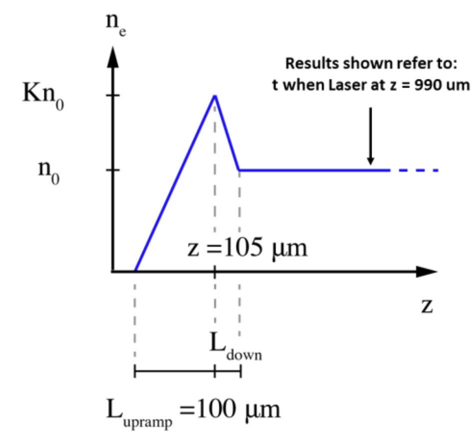


Low-energy LP Injector

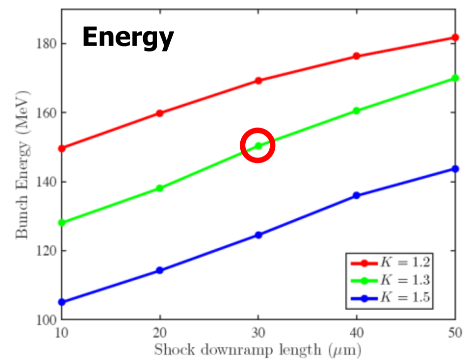
Horizon 2020

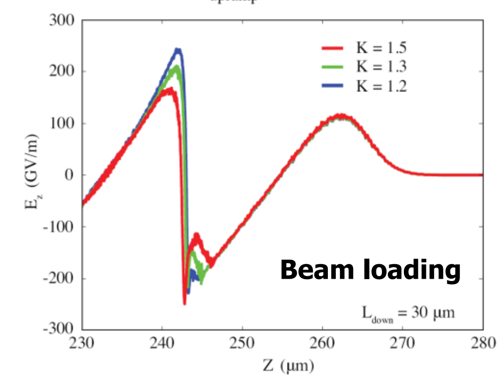
- Based on **shock injection**
  - Changing length & height of the downramp
  - Scan parameters (for $a_0 = 2.5$)
    $L_{downramp} = 10 – 50\ \mu m$, K = 1.2, 1.3, 1.5

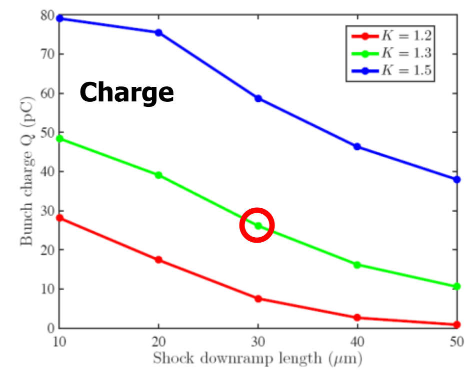
➢ 150 MeV 30 pC [LOA, F. Massimo]

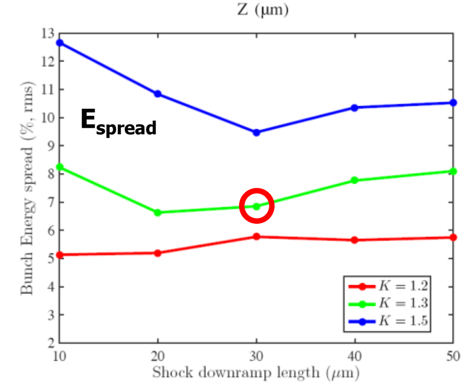


Laser	
Power	30 TW
Waist w_0	12 µm
a_0	2.5
Plasma	
Density n_0	$3 \times 10^{18}\ cm^{-3}$
Extracted beam @K=1.3 Ldr=30 µm	
Energy	150 MeV
Charge	30 pC
E spread rms	7 %
$\varepsilon_{N\,x,y}$ (mm.mrad)	0.8, 1.0





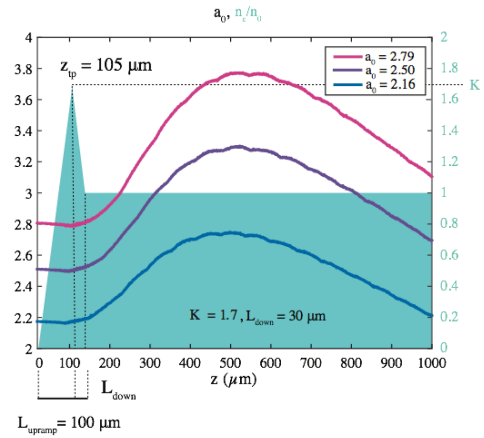




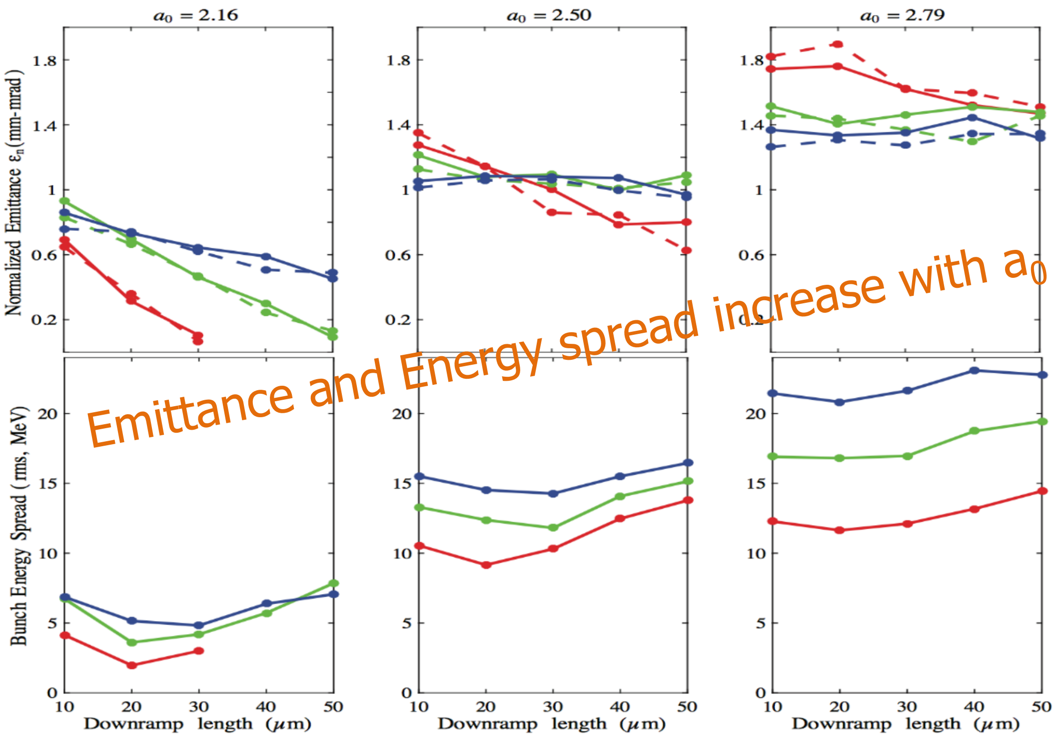
Low-energy LP Injector

- Based on shock injection
  - Changing also the laser energy
  - Scan parameters a_0 = 2.16, 2.5, 2.79
    $L_{downramp}$ = 10 – 50 μm , K = 1.3, 1.5, 1.7

➢ 150 MeV 30 pC [LOA, F. Massimo]



Laser	
Power	30 TW
Waist w_0	12 μm
a_0	2.5
Plasma	
Density n_0	3 x 10^{18} cm^{-3}
Extracted beam @K=1.3 Ldr=30 μm	
Energy	150 MeV
Charge	30 pC
E spread rms	7 %
$\varepsilon_{N\,x,y}$ (mm.mrad)	0.8, 1.0

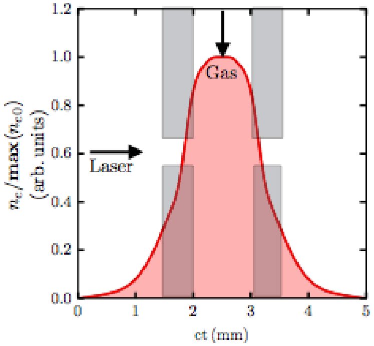


Emittance and Energy spread increase with a_0

Low-energy LP Injector

- Based on ionization injection
  - Ionization of inner shells of high Z atom (ex. N) at I_{peak} of laser pulse
  - Features: simple target configuration, moderate laser intensity, higher injected charge, emittance lower than self-injection scheme

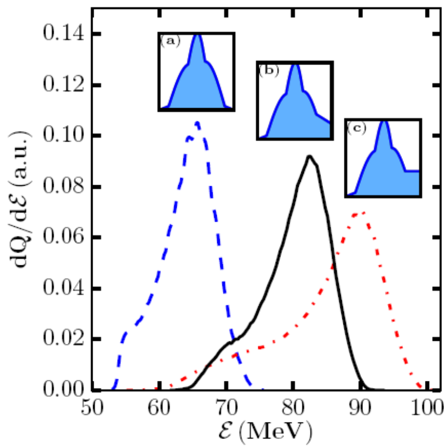
➢ LPGP parametric study [P. Lee et al]



ELISA density profile

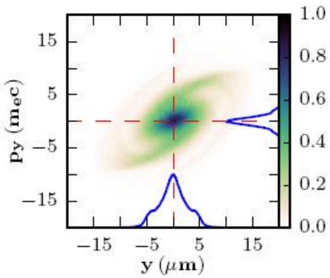
Laser	
Power	100 TW
Waist w_0	16 µm
Initial a_0	1.6
Plasma	
Density n_0 max	4 x 10^{18} cm^{-3}
Extracted beam (descending gradient)	
Energy	82.6 MeV
Charge	50 pC
E spread FWHM	11 %
$\varepsilon_{N\,x,y}$	0.33, 2.1 mm.mrad

Changing density profile with cst N_2 fraction (1%)



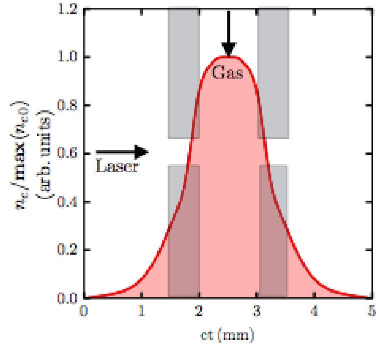
Density profile	E_{peak} (MeV)	ΔE/E (%)
ELISA	65.7	13.1
Descending gradient	82.6	11.0
Plateau	90.8	12.0

Bunch charge ~ 40-50 pC
Larger emittance in the laser polarisation plane $\varepsilon_{x,y}$ = 0.33, 2.1 µm



Low-energy LP Injector

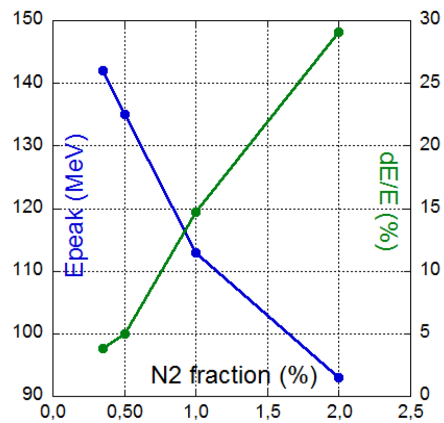
- Based on ionization injection
  - Ionization of inner shells of high Z atom (ex. N) at I_{peak} of laser pulse
  - Features: simple target configuration, moderate laser intensity, higher injected charge, emittance lower than self-injection scheme
    - ➢ LPGP parametric study [P. Lee et al]

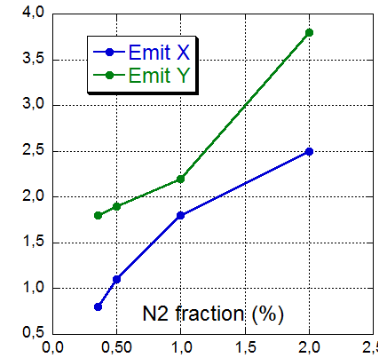


ELISA density profile

Laser	
Power	100 TW
Waist w_0	16 µm
Initial a_0	1.6
Plasma	
Density n_0 max	4×10^{18} cm^{-3}
Extracted beam L_{cell}1mm, 0.35% N_2	
Energy	142 MeV
Charge	27 pC
E spread rms	3.8 %
$\varepsilon_{N\,x,y}$	0.8, 1.8 mm.mrad

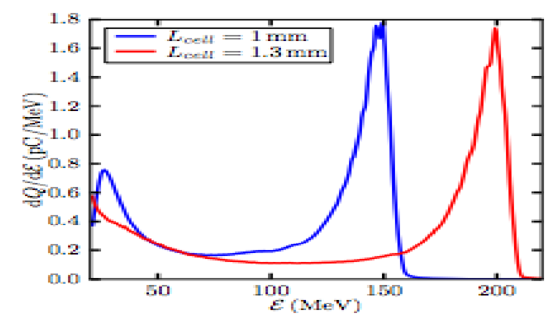
Changing N_2 fraction (ELISA profile)





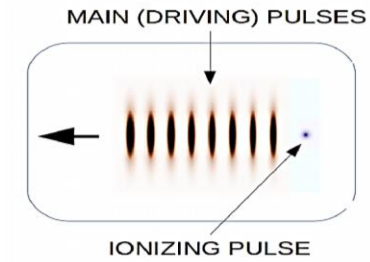
0.35% N_2 and longer cell (1→1.3 mm)

Energy	196 MeV
Charge	27 pC
E spread rms	3.2 %
$\varepsilon_{N\,x,y}$	1.3, 2.3 mm.mrad

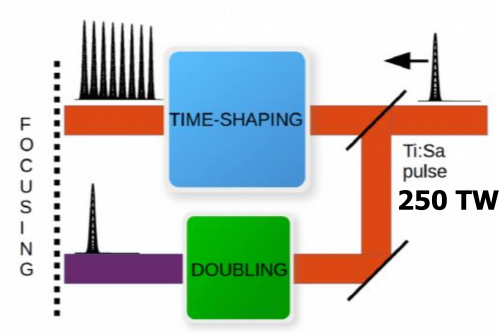


Multi-pulse ionization injection

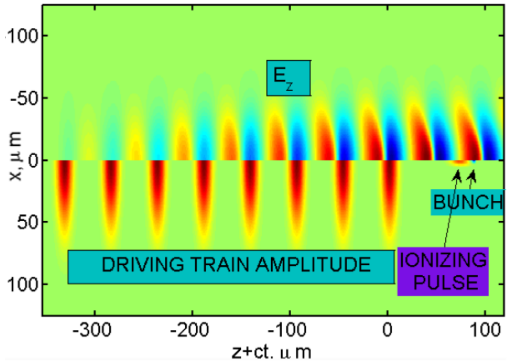
- Combination of multi-pulse resonant wakefield and ionization injection
  - A resonant multi-pulse drives a large-amplitude plasma wave
  - The wave traps electrons extracted by further ionization
  - ➢ INO-CNR study [P. Tomassini et al]

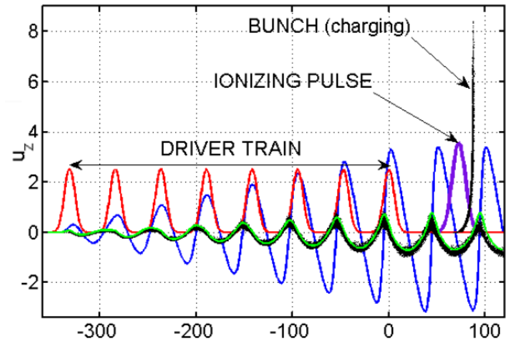


Drive Laser (x 8 pulses)	
a_0	0.64
Waist w_0	45 µm
Pulse length	30 fs
Ionization Laser (2nd harmonic)	
a_0	0.41
Waist w0	3.5 µm
Plasma	
Density n_0	5 x 10^{17} cm^{-3}
Length	6.5 mm
Extracted beam	
Energy	265 MeV
Charge	3.8 pC
E spread rms	0.65 %
$\varepsilon_{N\,x,y}$ (mm.mrad)	0.08, 0.02



Main Features:
- ✓ Ultra-low emittance
- ✓ Low energy spread
- ✓ Energy can be extended (laser guiding)





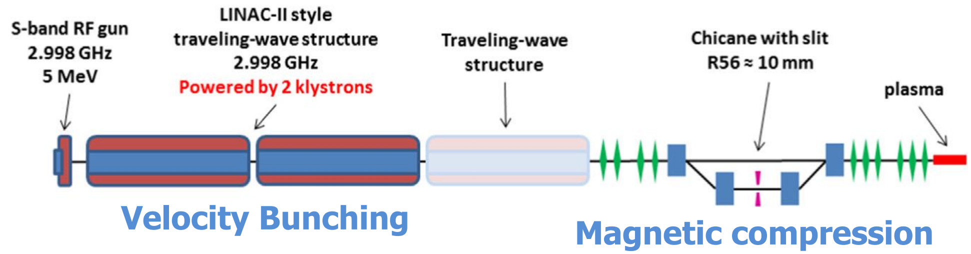
LP accelerating section

- **Beam injected from RF photo-injector (RFI)**
  - Inject the beam with expected parameters from RF photo-injector but at low charge ?
    - $E_b \sim 100$ MeV, $\sigma_z \leq 1$ fs, $\varepsilon_n < 1$ μm
      but $Q_b \sim 1$ pC
  - Inject the beam with expected parameters from RF photo-injector but at high energy ?
    - $Q_b \sim$ few 10's pC, $\sigma_z \sim$ 10-30 fs, $\varepsilon_n < 1$ μm
      but $E_b \sim$ few 100's MeV
- **Beam injected from optical injector (LPI)**
  - Short bunch but higher energy spread

LPAS fed by RFI

- External injection low charge, sub-fs @SINBAD
  - Moderate laser power, [M. Weikum et al, Desy]

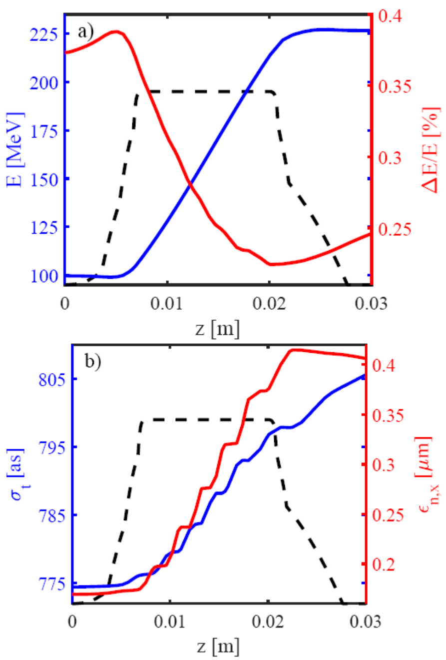
Injector exit	
Energy	~ 100 MeV
Charge	0.7 pC
Bunch length rms	0.77 fs
Emittance Norm	≤ 0.2 μm
Laser parameter	
Power	~200 TW
Waist w_0	42.5 μm
a_0	1.8
Pulse length FWHM	25 fs
Plasma	
density n_0	10^{17} cm^{-3}
Length (plateau)	1.25 cm



ARES Linac

Though not a working point in EuPRAXIA

without guiding → 224 MeV



- **Ultrashort bunch** ⇒ small energy spread but limited by the uncorrelated spread due to transverse gradient of the wakefields
- Careful matching required with ~ 1 cm long density upramp
- longer plasma (>10cm) to achieve 1 GeV level with laser guiding but increase of emittance and Espread due to numerical dephasing

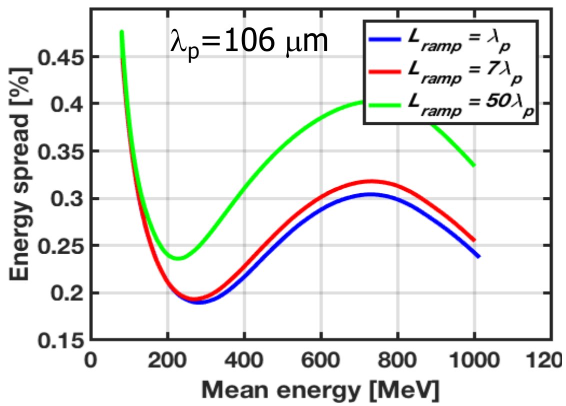
2D OSIRIS simulation (Lehe Solver with anti-Cherenkov stencil)

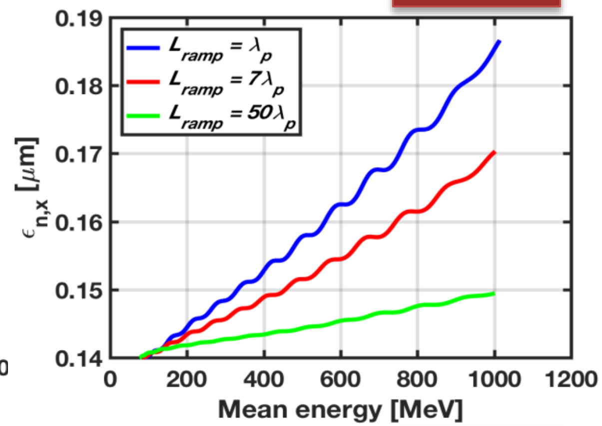
LPAS fed by RFI

- External injection low charge, sub-fs @SINBAD
  - ➢ High laser power 100 J [E. Svystun, Desy]

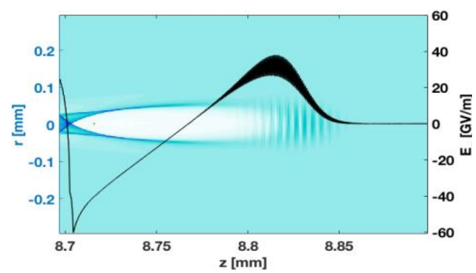
Injector exit	
Energy	83.5 MeV
Charge	0.74 pC
Bunch length rms	0.87 fs
Emittance Norm	0.14 μm
Laser parameter (100 J)	
Power	953.5 TW
Waist w_0	64 μm
a_0	3.1
Pulse length FWHM	100 fs
Plasma	
density n_0	10^{17} cm^{-3}
Length (plateau)	25 mm (1 GeV) 65 mm (2 GeV)

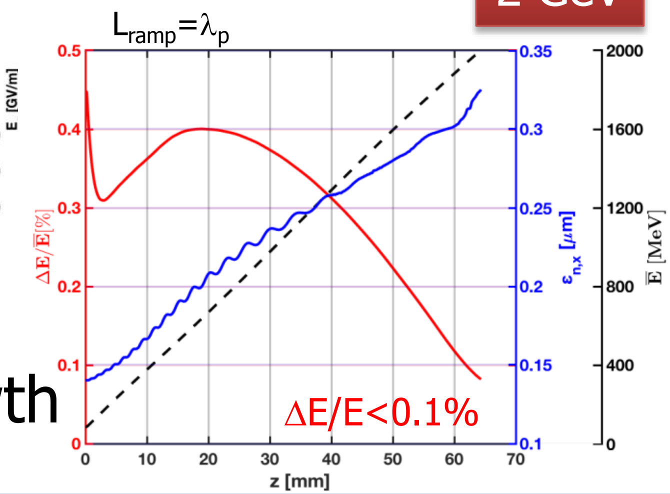
1 GeV





2 GeV

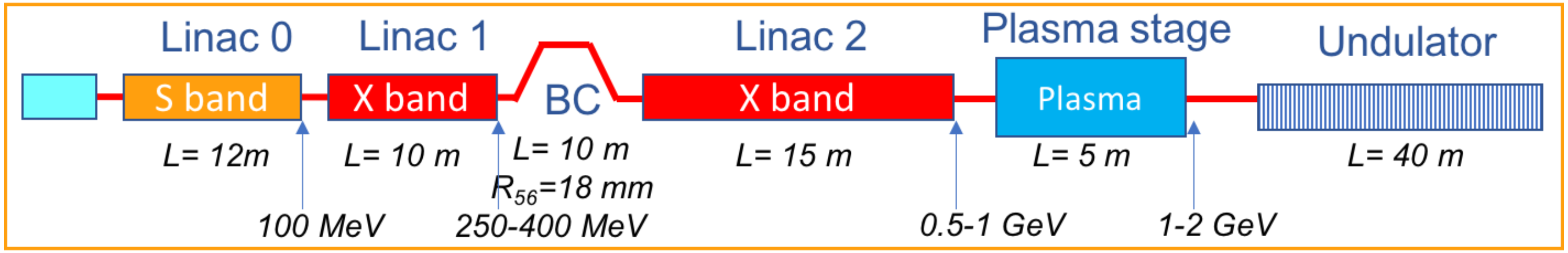




Injection phase and ramp optimisation

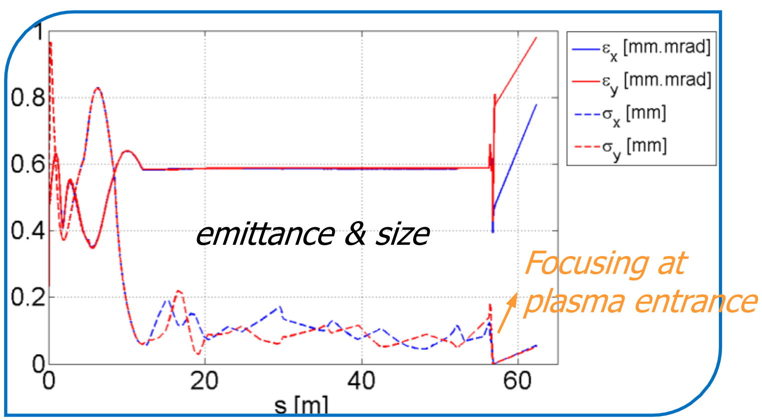
$\Rightarrow$ small energy spread & emittance growth

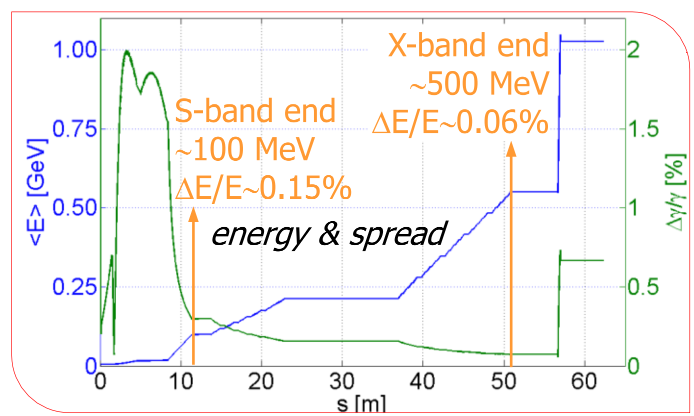
- 1 GeV from high-energy RF injector
  results of EuPRAXIA@SPARC_LAB studies



S-Band photo-injector ~100 MeV + X-band ~**500 MeV**

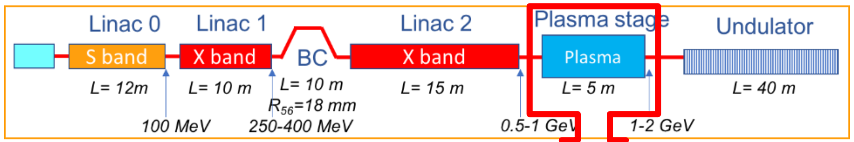
to generate high-quality beams: 1 bunch for LPA scheme
or 1 witness bunch + 1 driving bunch for BPA scheme

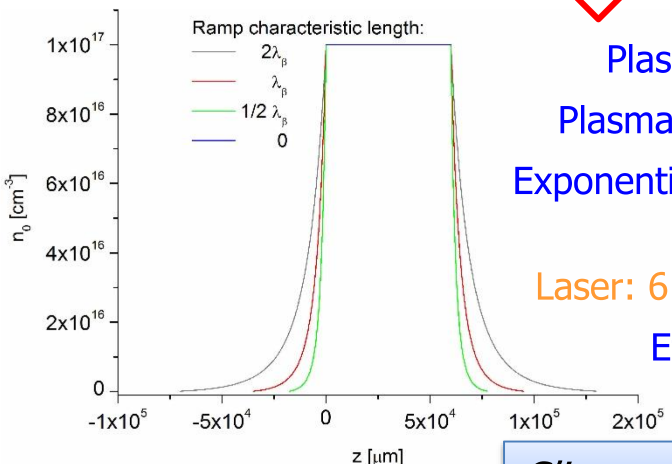




Laser driven PA fed by RFI

Horizon 2020





Plasma density: 10^{17} cm^{-3}

Plasma plateau length: 6 cm

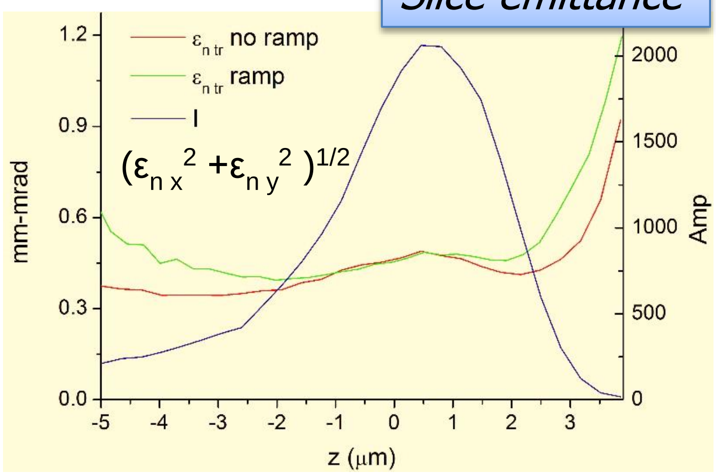
Exponential ramp characteristic length $\lambda_\beta/2$ = 2.5 mm

Laser: 6.13 J, 112 fs, a_0=1.15

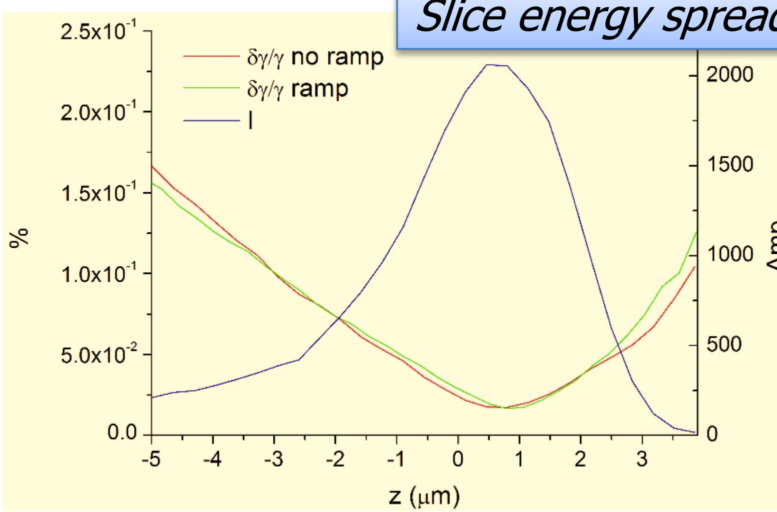
Effective Eacc: 9 GV/m

	Input	Output w/o ramp	Output with ramp
E [GeV]	536	1.060	1.035
ΔE/E [%]	0.07	1.2	0.07
$\hat{I}_{FWHM}$ [kA]	1.8	1.8	1.8
Q [pC]	30	27	27
$\sigma_{z\ rms}$ [μm]	3.7	3.3	3.3
$\sigma_{z\ FWHM}$ [μm]	3.3	3.2	3.2
ε_n [mm.mrad]	0.44	0.47	0.47
$\hat{I}_{slice}$ [kA]	2.1	2.1	2.1

Slice emittance

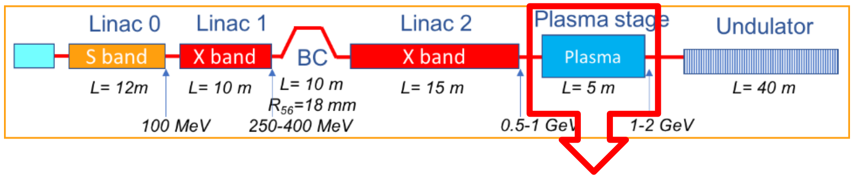


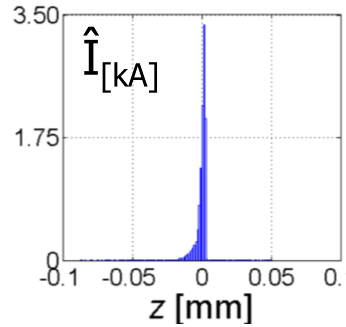
Slice energy spread



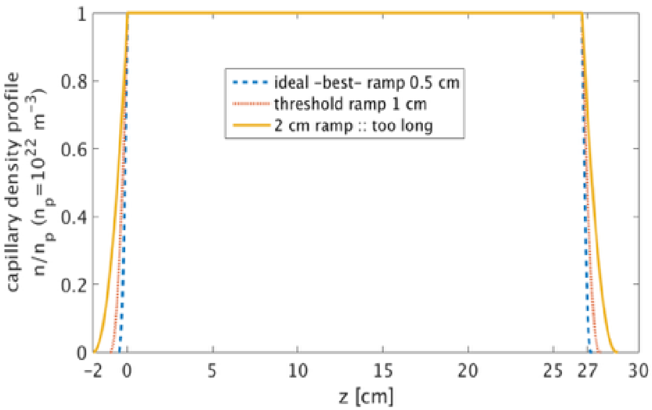
Simulations with Qfluid [P. Tomassini and A.R. Rossi, Plas. Phys. Cont. Fus. 58, 034001 (2016)]

Beam driven PA fed by RFI





witness	entrance	exit
E [GeV]	0.5	1
σ_E [%]	0.06	0.73
Q [pC]	29	29
$\sigma_{z\ rms}$ [μm]	3.5	3.3
ε_x [μrad]	0.4	0.48
ε_y [μrad]	0.4	0.81
σ_x [μm]	0.73	1.2
σ_y [μm]	1.3	1.2



Plasma density: 10^{16} cm^{-3}

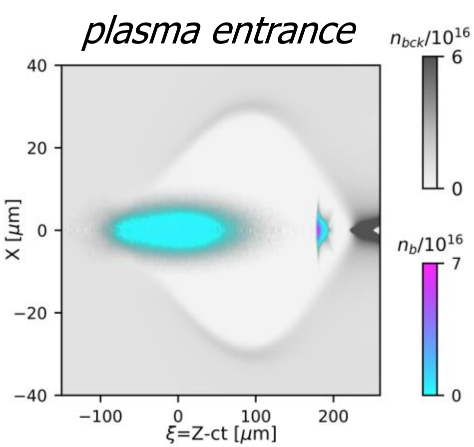
Plasma plateau length: 27 cm

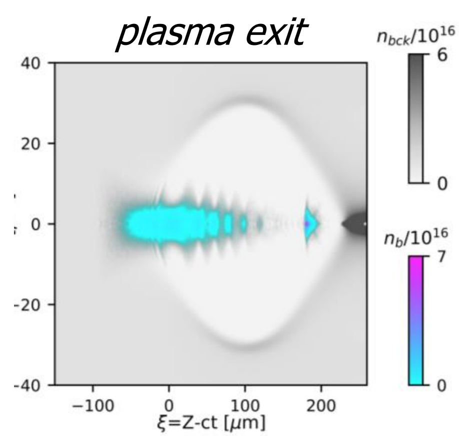
Ramp length (ideal) = 5 mm

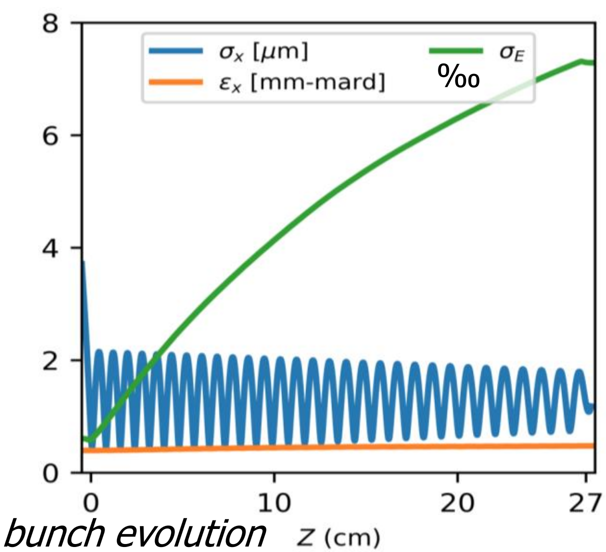
Driver bunch: Q_b=200 pC

σ_z=50 μm, σ_E=0.1%, $\varepsilon_{x,y}$=3 μm

Effective Eacc: 1.85 GV/m







witness bunch evolution

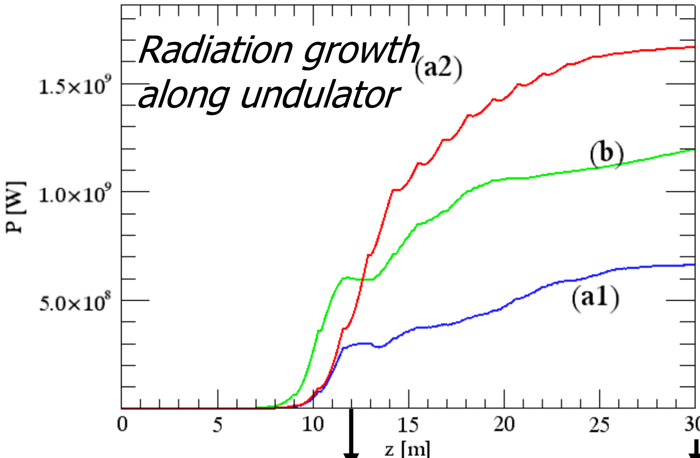
Simulations with Architect

FEL Genesis simulation

Undulator λ_u=1.5 cm

Laser-driven plasma acc.

Radiation λ=2.7 nm
E_{phot}=0.45 keV



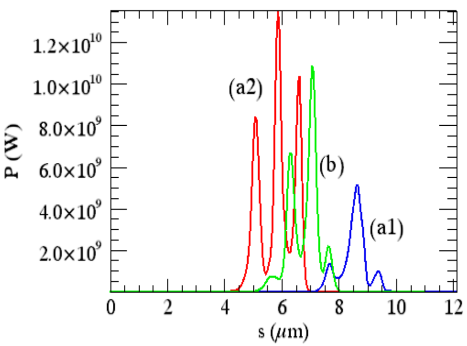
without ramps
with tapering

with ramps

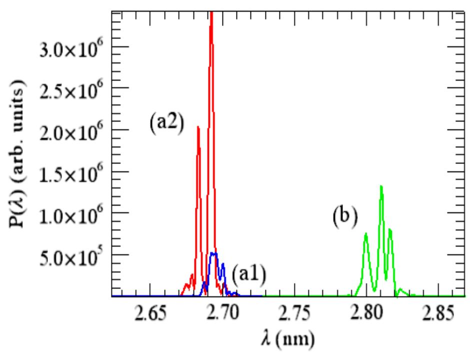
without ramps

Number of photons

@ 12 m	@ 30 m
2.5 10^{11}	6.4 10^{11}
3 10^{11}	5.2 10^{11}
1.6 10^{11}	3.6 10^{11}



Power density @ 15 m
Quasi-single structure

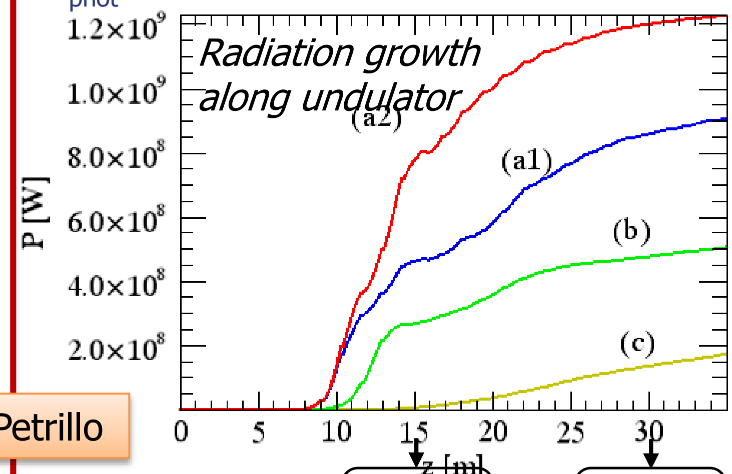


Spectral density @ 15 m
Quasi-single spike structure

Vittoria Petrillo

beam-driven plasma acc.

λ=2.78 nm
E_{phot}=0.44 keV



without ramps
with tapering

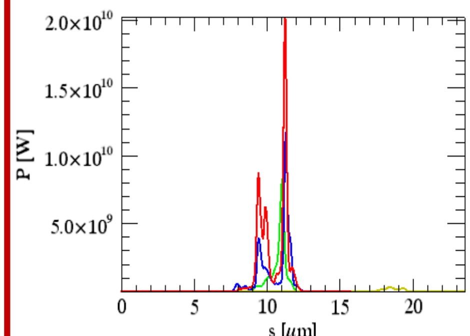
without ramps

with ramps
5 mm

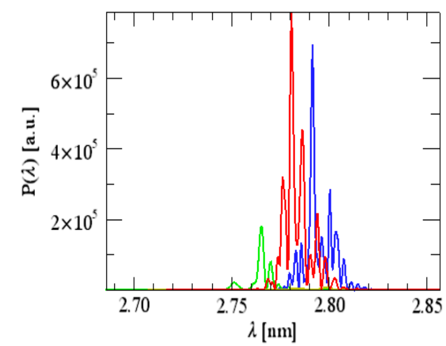
10 mm

Number of photons

@ 15 m	@ 30 m
5 10^{11}	8 10^{11}
3.6 10^{11}	6 10^{11}
2 10^{11}	3.5 10^{11}



Power density @ 15 m
Quasi-single structure



Spectral density @ 15 m
Quasi-single spike structure

• Quasi-linear regime with plasma channel

– Main parameters inferred from analytical expressions (checked by WARP 3D simulations + boosted frame)

$$n(r) = n_0\left(1 + \frac{\Delta n}{n_0}\frac{r^2}{r_0^2}\right)$$

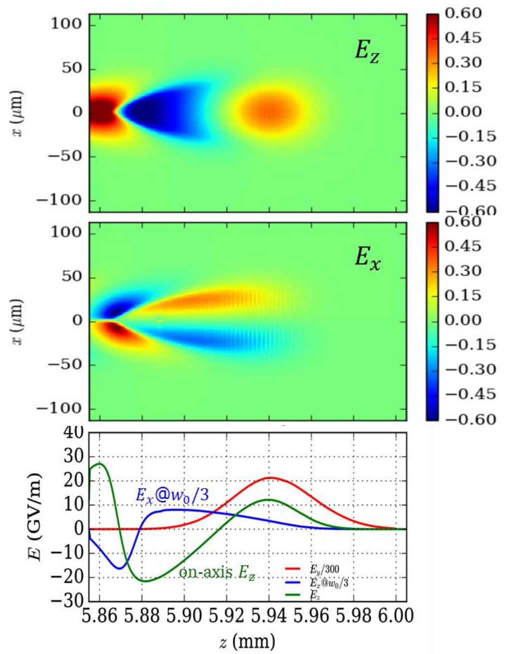
– Energy gain

$$\Delta\gamma_b = \frac{2}{\pi}k_p L_{dp}\frac{E_{z,max}}{E_0}\left[\left(1+\frac{L_{acc}}{L_{pd}}\right)\sin\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right)+\frac{2}{\pi}\frac{L_{dp}}{L_{pd}}\left(\cos\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right)-1\right)\right] = f(k_p, a_0, w_0)$$

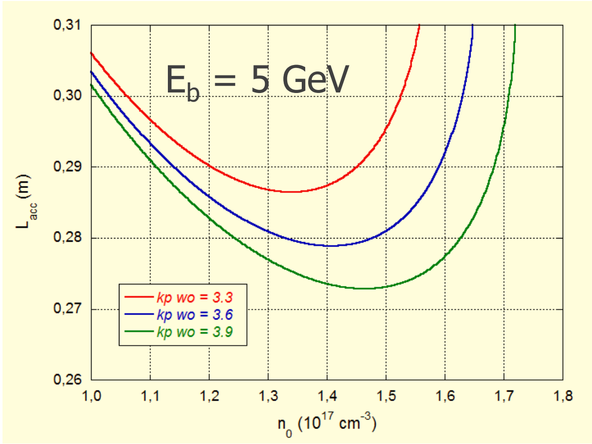
L_{pd} power depletion length
L_{dp} dephasing length
k_p plasma wavenumber

➢ 1-5 GeV 30 pC [CEA, X. Li / A. Mosnier]

Laser	
strength a_0	$\sqrt{2}$
spot size w_0	45 μm
rms pulse length σ_t	64.5 fs
peak power	136 TW
energy	15.5 J
Plasma	
Density n_0	$1.5\ 10^{17}$ cm^{-3}
channel depth $\Delta n/\Delta n_c$	~ 0.5
acc. length L_{acc}	~ 30 cm
Injected beam	
energy	150 MeV
$\varepsilon_{N\ x,y}$	1 mm.mrad
charge	Low (1 pC)
Bunch size $\sigma_{x,y}$	1.3 μm



→ Matched beam to preserve the emittance



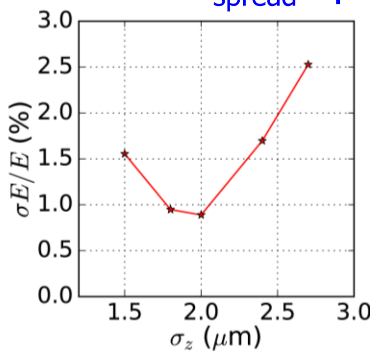
For a given energy gain, laser strength and norm. spot size, there is a plasma density value which minimizes the plasma channel length

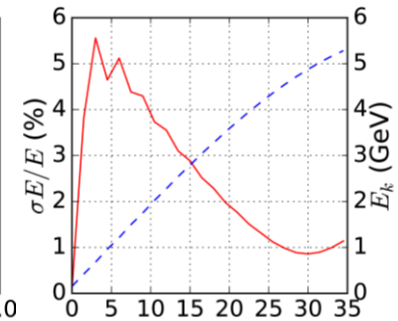
LPAS fed by LPI

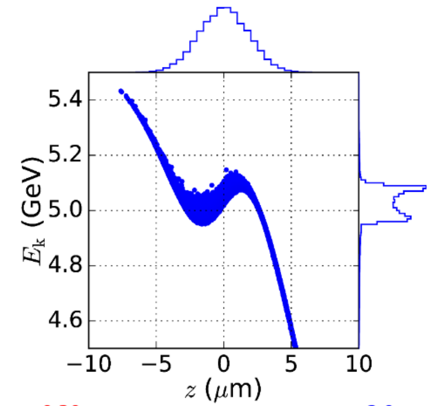
- Quasi-linear regime with plasma channel
  - **Correlated energy spread**: induced by wakefield curvature + beam-loading
    - beam loading compensation → bunchlength optimisation (further reduced by bunch shaping)
  - **Slice energy spread**: induced by radial dependance of
    - accelerating field [negligible when driver (beam or laser) >> bunch size]
    - longitudinal field excited by the accelerated bunch [cannot be neglected] $n_b \sim 10^{19}$ cm^{-3} >> n_0

Laser	
strength a_0	$\sqrt{2}$
spot size w_0	45 µm
rms pulse length σ_t	64.5 fs
peak power	136 TW
energy	15.5 J
Plasma	
Density n_0	1.5 10^{17} cm^{-3}
channel depth $\Delta n/\Delta n_c$	~ 0.5
acc. length L_{acc}	~ 30 cm
Injected beam	
Energy	150 MeV
Energy spread	3 %
$\varepsilon_{N\ x,y}$	1 mm.mrad
Charge	30 pC
Bunch size $\sigma_{x,y}$	1.3 µm

Correlated E_{spread} optimization



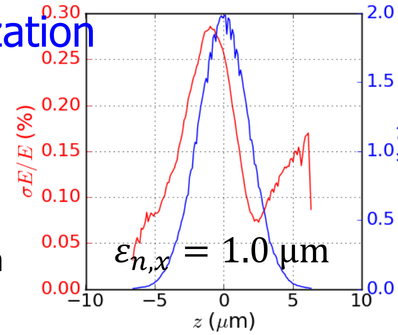


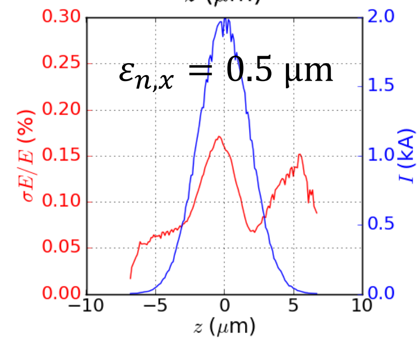


Slice E_{spread} minimization

- Bunch size ↘
- Plasma density ↘

ex. $10^{17} \rightarrow 10^{16}$ cm^{-3} needs ~1m plasma length to reach 5 GeV beam





Conclusions

- Numerous simulations carried out within the EuPRAXIA framework
- Parametric studies of Laser Plasma Injector
  - high energy (self-injection), low energy (down-ramp, shock injection, ionization, multi-pulse)
- Plasma accelerator section
  - Beam injected from RF injector (high energy) and LP injector (low energy)
- Next steps
  - End-to-end simulations (started at SparcLab)
  - Error study (Introduce various fluctuations: laser imperfections, plasma density, alignment, …)

acknowledgments

Big thanks to all members of the EuPRAXIA WP2
For the great job made during these ~ 18 months, and
For providing me all material shown in this presentation

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END