EuPRAXIA, A STEP TOWARD A PLASMA-BASED ACCELERATOR WITH HIGH BEAM QUALITY

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EuPRAXIA Consortium

16 Participants

25 Associated Partners

Private companies

EuPRAXIA scope

From Acceleration to Accelerator
From Proof of principle to User's Facility

Mission: Produce a Conceptual Design Report for the world's first

Simultaneously !

- high energy ~GeV plasma-based electron accelerator
  driven by laser or electron beam
- with "industrial quality"
  24/7 user operation
  high reliability, reproducibility
  high repetition rate ≥ 10 Hz toward 100 Hz
- with high beam quality and high beam charge
- with user areas: FEL & HOPA

Simultaneously !

EuPRAXIA requirements

Critical parameters of the electron beam required at Injection or Acceleration stages

OBJECTIVE:

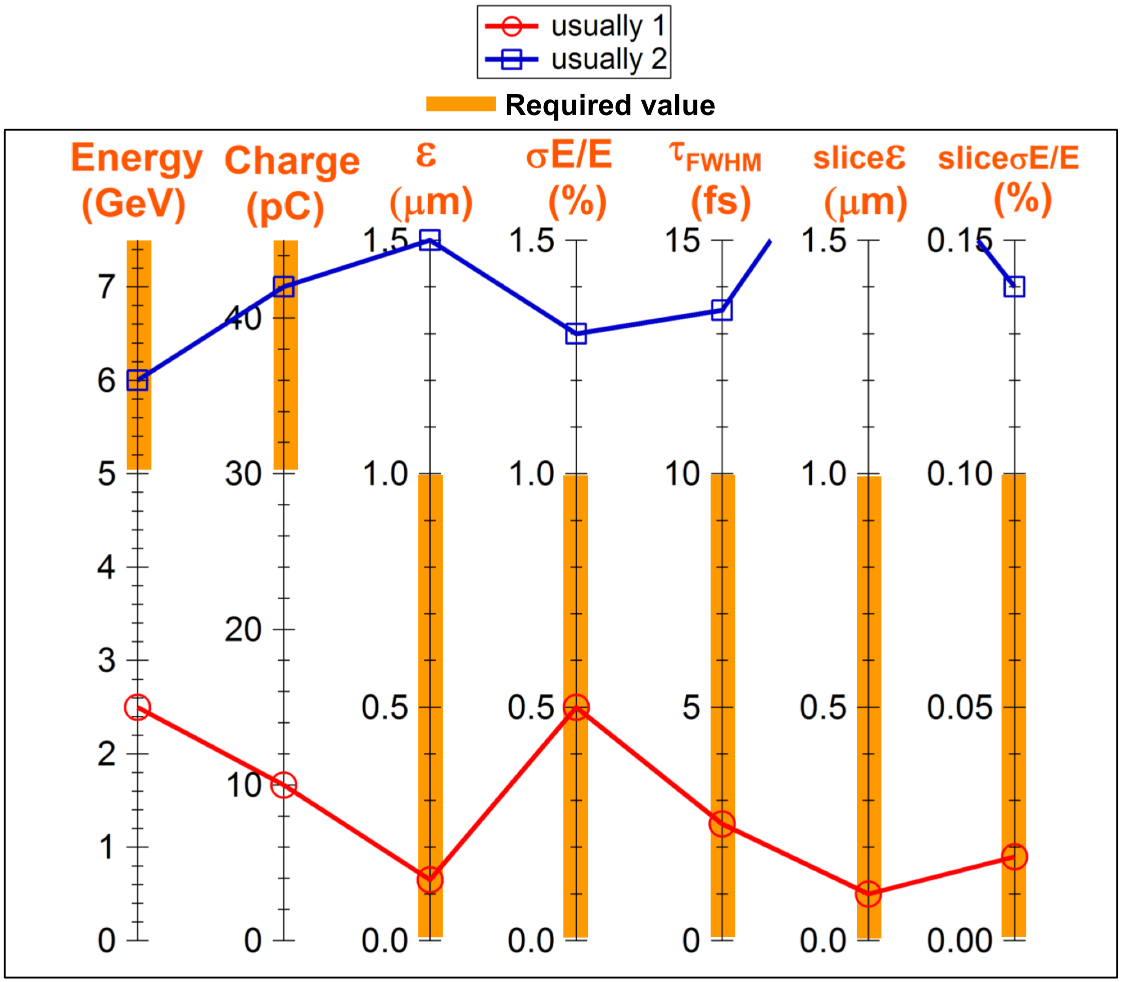
- Provide beam at 5 GeV meeting 'perfectly' FEL and HOPA requirements

- Provide also beam at 1 GeV 'usable' for FEL and HOPA as a 'commissioning' step

Parameter	LP Injector exit	RF Injector exit	Accelerator exit
E	150 MeV	250-500 MeV	5 GeV (1 GeV)
Q	30 pC	30 pC	30 pC
τ (FWHM)	10 fs	10 fs	10 fs
σ_E/E	5%	0.2 %	1%
$\sigma_{E,s}/E$	t.b.d.	t.b.d.	0.1 %
ε_n	1 mm.mrad	1 mm.mrad	1 mm.mrad
$\varepsilon_{n,s}$	t.b.d.	t.b.d.	1 mm.mrad

at the applications!

Beam parameters at 5 GeV at the user's doorstep



"Accelerator" approach

"Physics experiment " approach : often built around a laser facility

"Accelerator" approach : like for a conventional accelerator

a) Definition of the desired beam parameters (TLR)

b) Large exploration / optimization of beam inject./accelerat. in plasmas

c) Selection of the appropriate configurations

d) Optimization of beam extraction, transport

e) Estimation of sensitivity to errors

f) Determination of needed laser and plasma systems

Issues : for plasma-based accelerator
- Simulations are very time consuming
- Many simulation codes → reliability, robustness ?

In the following …

1. Inj./Acc. configurations studied. Results and Selections
2. Lessons learned: how to obtain high beam energy AND charge AND quality
3. Optimization of beam extraction and transport
4. Estimation of sensitivity to errors
5. Specifications for plasma and laser systems

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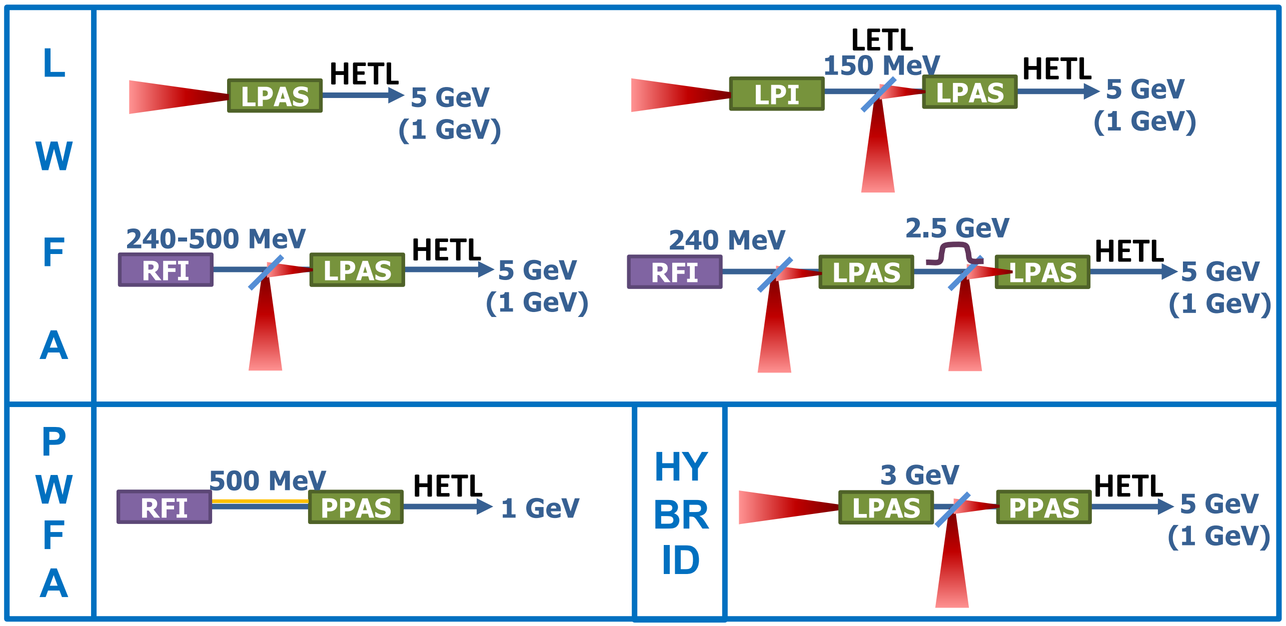
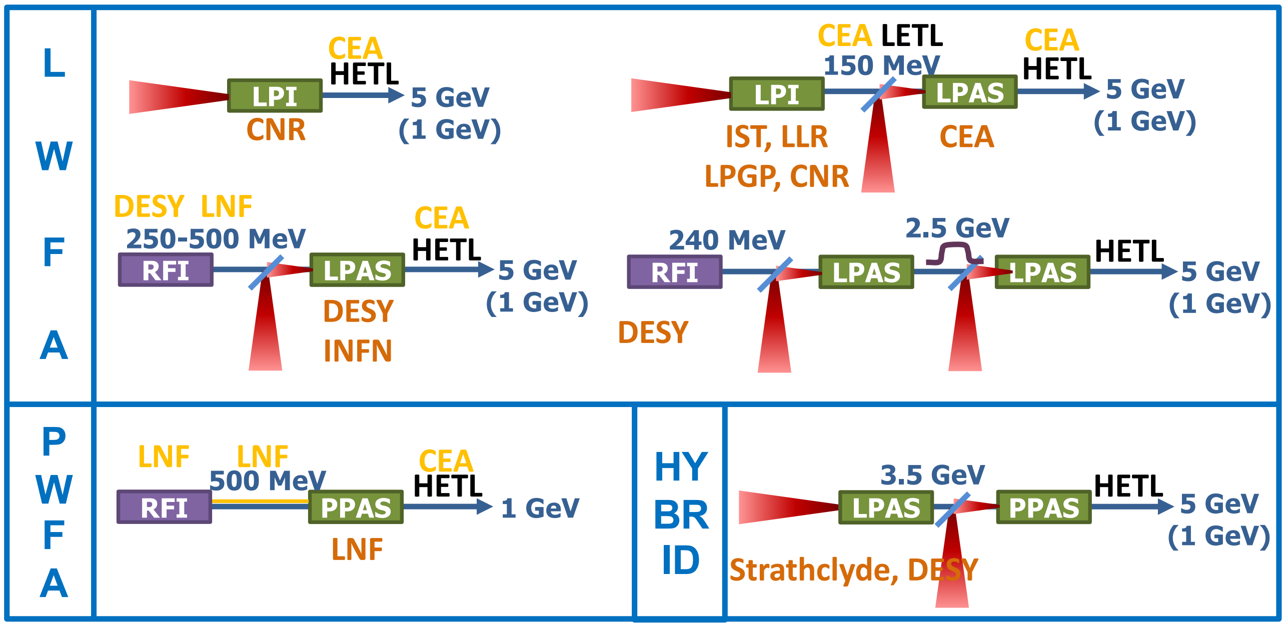
Inj. / Accel. schemes studied



Inj. / Accel. schemes studied



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Inj. / Accel. techniques studied

RFI 240 MeV	S-band, RF & Magn.compression
RFI 500 MeV	S-band & X-band, Comb technique
LPI 150 MeV	Wave-breaking injection and nonlinear regime Shock-front injection and blow-out regime Ionization injection and nonlinear regime Downramp injection and blow-out regime Resonant Multiple Ionization Injection (ReMPI)
LPAS 5 GeV	ReMPI, 1 LPAS Quasi-linear regime, injector+LPAS Blow-out regime, injector +2 LPAS+chicane
PPAS 1 GeV	Weakly-nonlinear regime
LPAS-PPAS	Trojan Horse Injection and blow-out regime Wakefield Induced Ionization Injection and blow-out regime

Inj. / Accel. techniques studied

RFI 240 MeV	S-band, RF & Magn.compression	ASTRA
RFI 500 MeV	S-band & X-band, Comb technique	Tstep, Elegant
LPI 150 MeV	Wave-breaking injection and nonlinear regime	SMILEI
	Shock-front injection and blow-out regime	CALDER-C
	Ionization injection and nonlinear regime	Warp
	Downramp injection and blow-out regime	OSIRIS
	Resonant Multiple Ionization Injection (ReMPI)	ALaDYN, QFluid
LPAS 5 GeV	ReMPI, 1 LPAS	ALaDYN, QFluid
	Quasi-linear regime, injector+LPAS	FBPIC, QFluid, Warp
	Blow-out regime, injector +2 LPAS+chicane	FBPIC, ASTRA, CSRtrack
PPAS 1 GeV	Weakly-nonlinear regime	Architect
LPAS-PPAS	Trojan Horse Injection and blow-out regime	VSim
	Wakefield Induced Ionization Injection and blow-out regime	OSIRIS

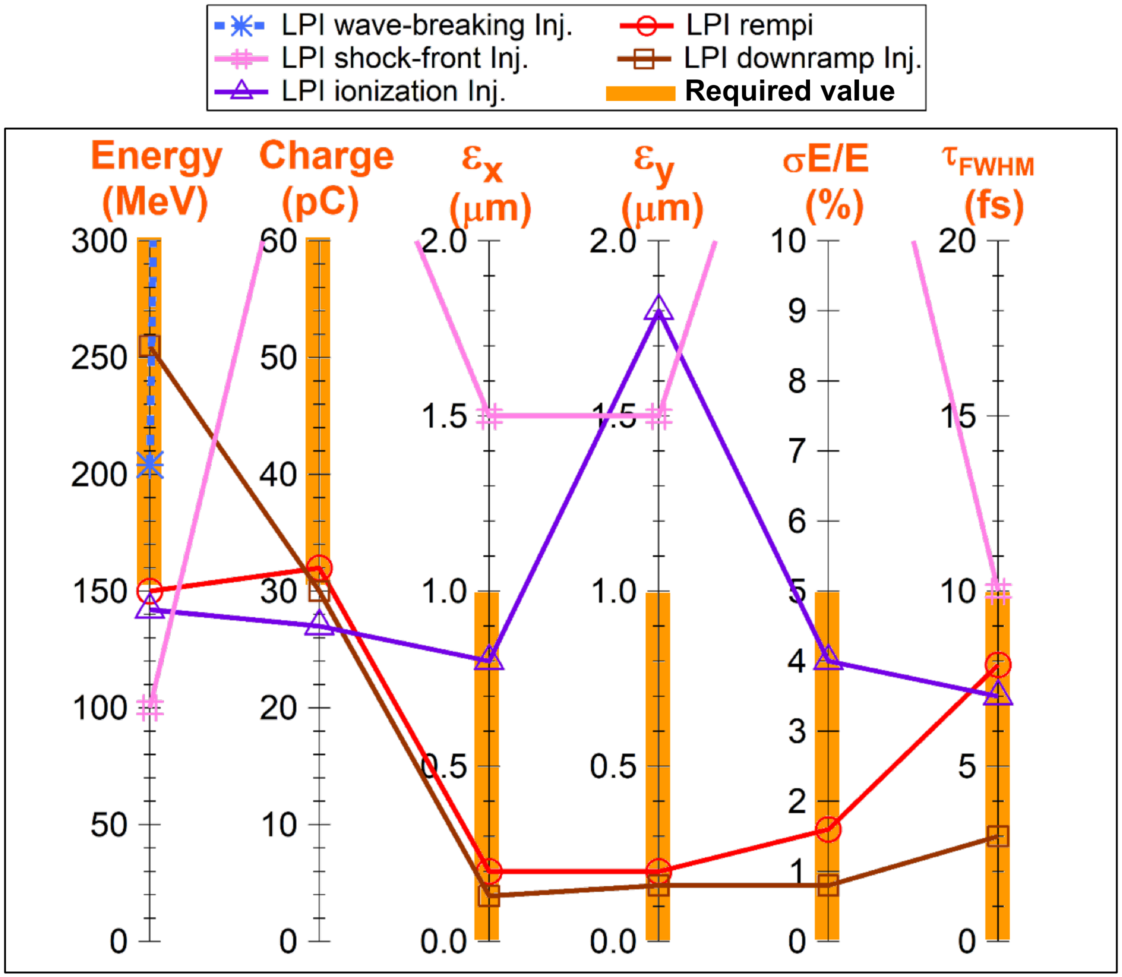
Published results

1. The resonant multi-pulse ionization injection, P. Tomassini, S. De Nicola, L. Labate, P. Londrillo, R. Fedele, D. Terzani, L. A. Gizzi, Physics of Plasmas, 24 , 10, 103120, doi: 10.1063/1.5000696 (2017).
2. Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams, G.G. Manahan, A.F. Habib et al., Nat. Commun. 8, 15705 doi: 10.1038/ncomms15705 (2017).
3. Electron beam transfer line design for plasma driven Free Electron Lasers, M. Rossetti Conti, A. Bacci, A. Giribono, V. Petrillo, A.R. Rossi, L. Serafini, C. Vaccarezza, Nuclear Inst. and Methods in Physics Research A 909, 84-89 (2018).
4. Design of a 5 GeV Laser Plasma Accelerating Module in the Quasi-linear Regime, X. Li, A. Mosnier, P. A. P. Nghiem, Nuclear Inst. and Methods in Physics Research A 909, 49-53 (2018).
5. Toward Low Energy Spread in Plasma Accelerators in Quasi-linear Regime, X. Li, P. A. P. Nghiem, A. Mosnier, Phys. Rev. Accel. Beams, 21, 111301 (2018).
6. Plasma boosted electron beams for driving Free Electron Lasers, A. R. Rossi et al., Nuclear Inst. and Methods in Physics Research, A 909, 54 (2018).
7. Optimization of laser-plasma injector via beam loading effects using ionization-induced injection, P. Lee, G. Maynard, T. L. Audet, B. Cros, R. Lehe and J.-L. Vay, Phys. Rev. Accel. Beams, 21, 052802 (2018).
8. Preserving emittance by matching out and matching in plasma wakefield acceleration stage, X. Li, A. Chancé, P. A. P. Nghiem, Phys. Rev. Accel. Beams, 22, 021304 (2019).
9. Compact multistage plasma-based accelerator design for correlated energy spread compensation, A. Ferran Pousa, A. Martinez de la Ossa, R. Brinkmann, and R. W. Assmann, Phys. Rev. Lett. 123, 054801 (2019).
10. High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, P. Tomassini, D. Terzani, F. Baffigi, F. Brandi, L. Fulgentini, P. Koester, L. Labate, D. Palla and L. A. Gizzi, Plasma Phys. Control. Fusion, in press
11. Hybrid LWFA|PWFA Staging as a Beam Energy and Brightness Transformer: Conceptual Design and Simulations, A. Martinez de la Ossa, R. W. Assmann, M. Bussmann, et al., Philos. Trans. Roy. Soc. A, in press
12. High quality electron bunches for a multi-stage GeV accelerator with the Resonant Multi-Pulse Ionization injection, P. Tomassini, D. Terzani, L. Labate, G. Toci, A. Chancé, P. A. P. Nghiem and L. A. Gizzi, Phys. Rev. Accel. Beams, in press
13. T. Silva et al., Plasma down-ramp based electron injector for plasma based accelerators, T. Silva et al., Plasma Phys. Control. Fusion, in press

And others ………….

Beam parameters obtained at 150 MeV

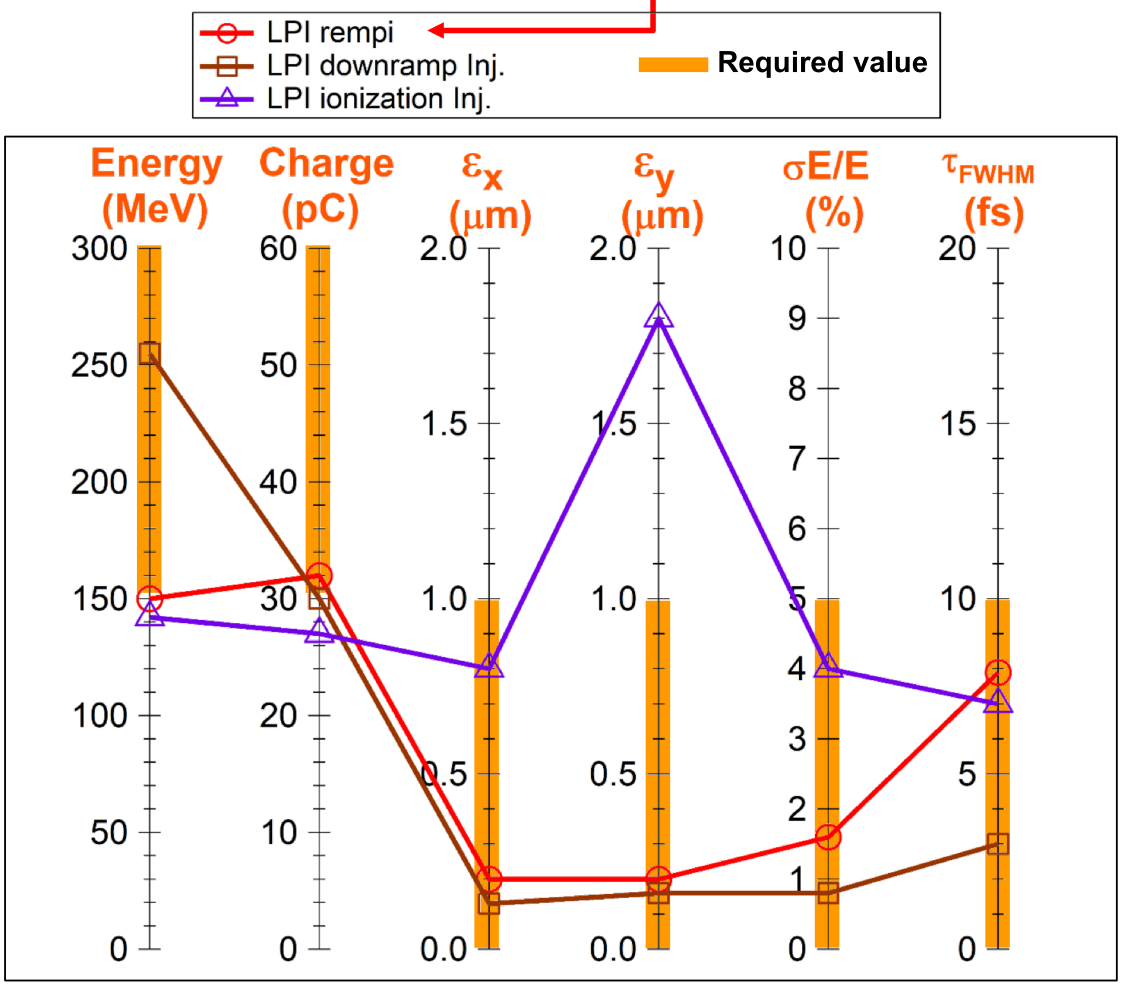
All the configurations



Beam parameters obtained at 150 MeV

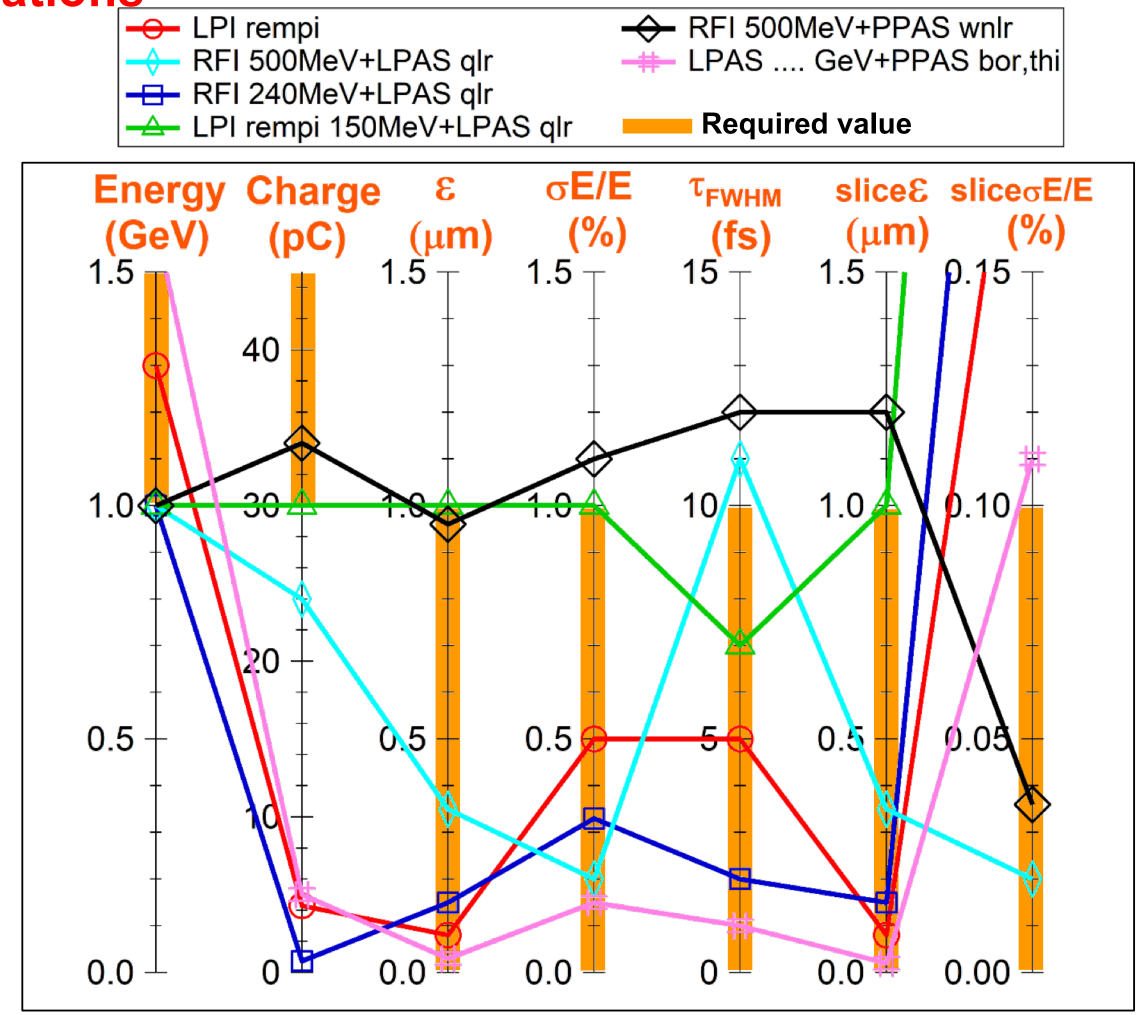
Configurations closest to the requirements

Selected for start-to-end simulations



Beam parameters obtained at 1 GeV

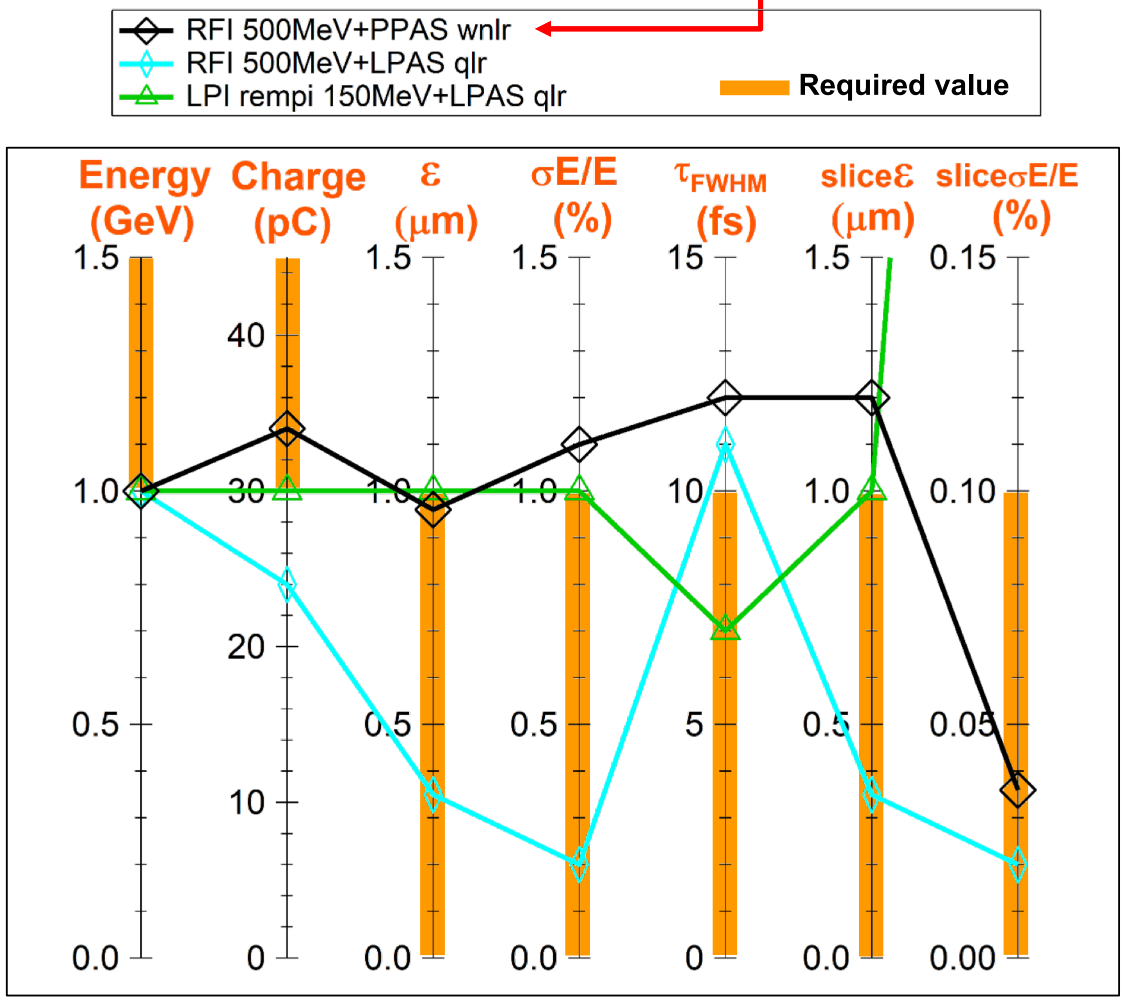
All the configurations



Beam parameters obtained at 1 GeV

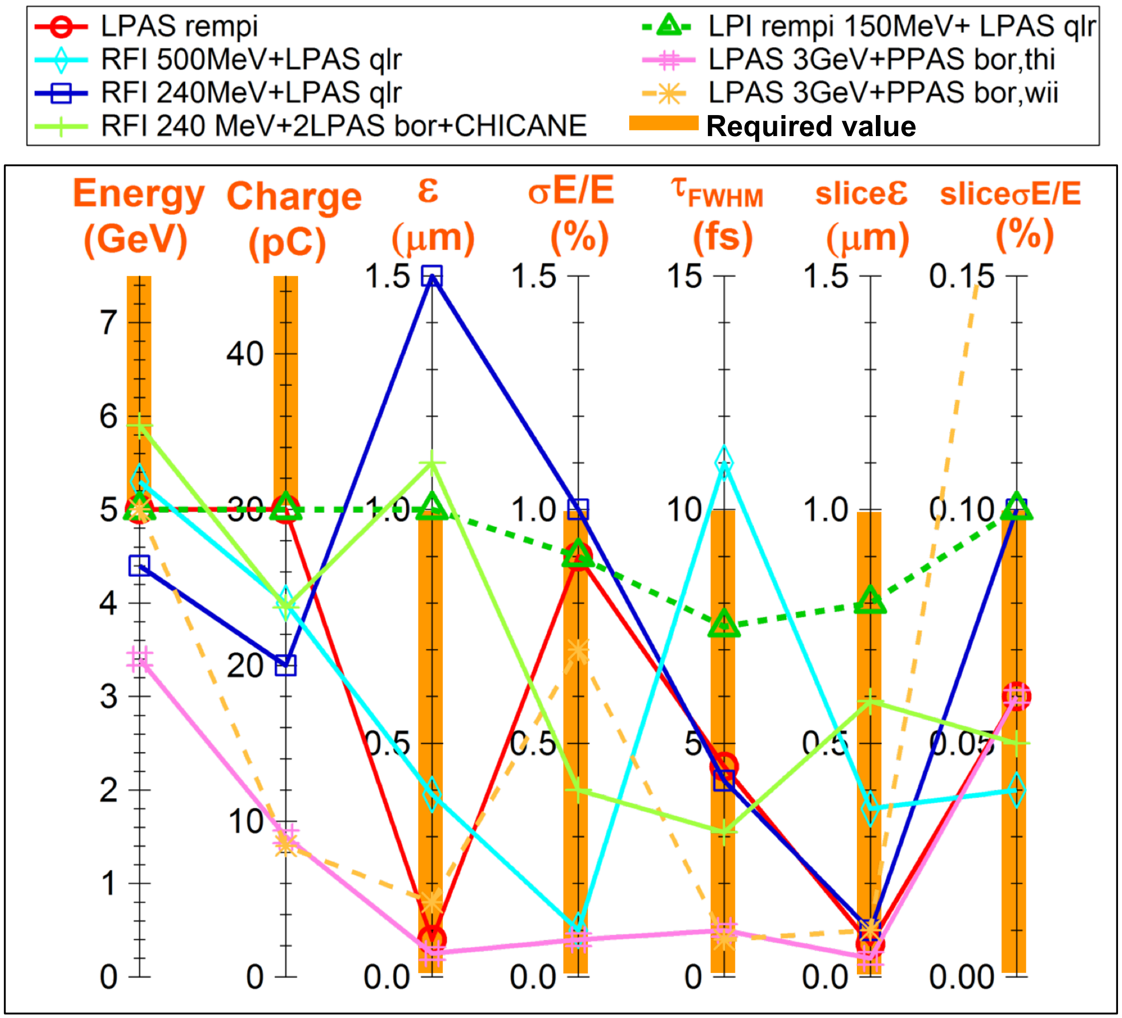
Configurations closest to requirements

Selected for start-to-end simulations



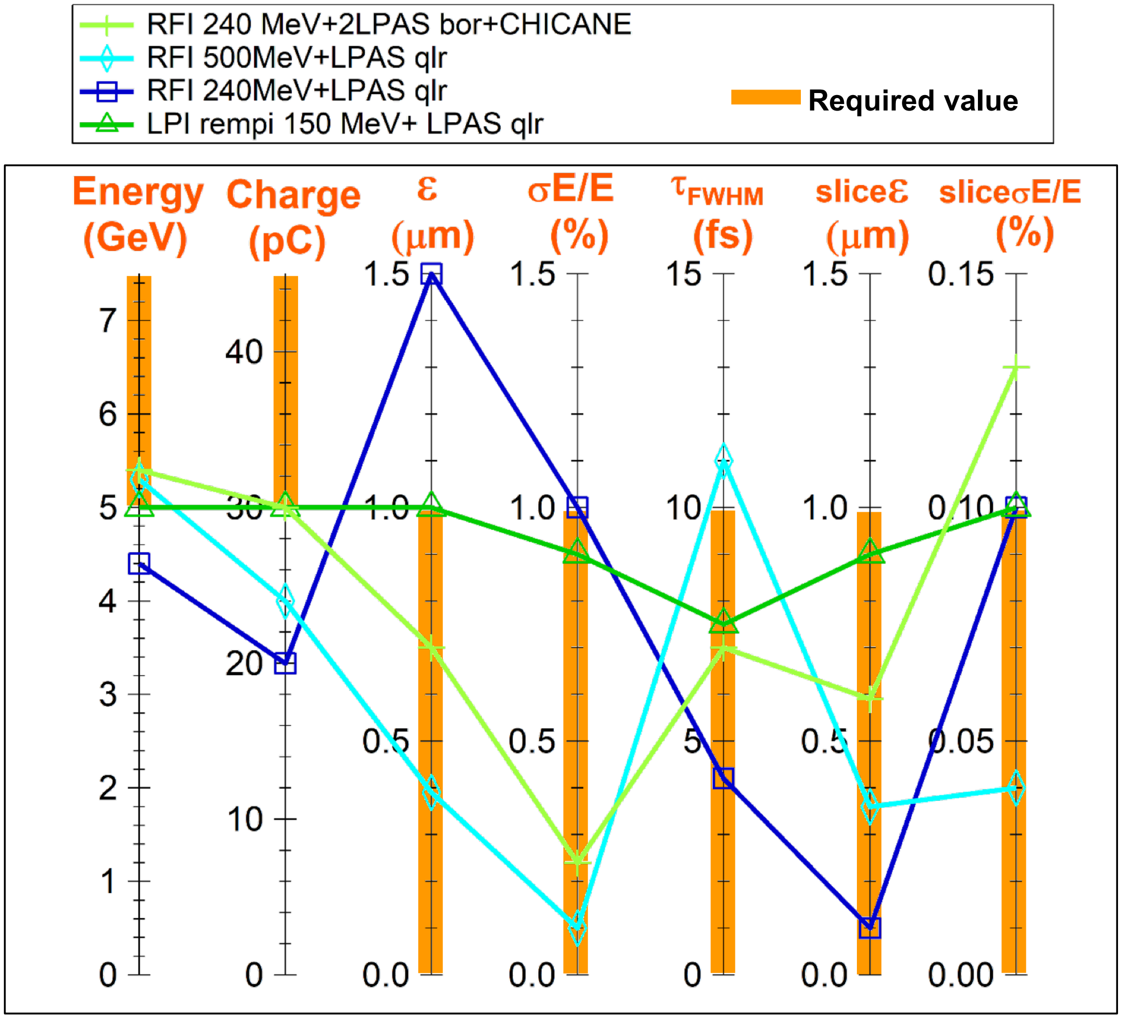
Beam parameters obtained at 5 GeV

All the configurations



Beam parameters obtained at 5 GeV

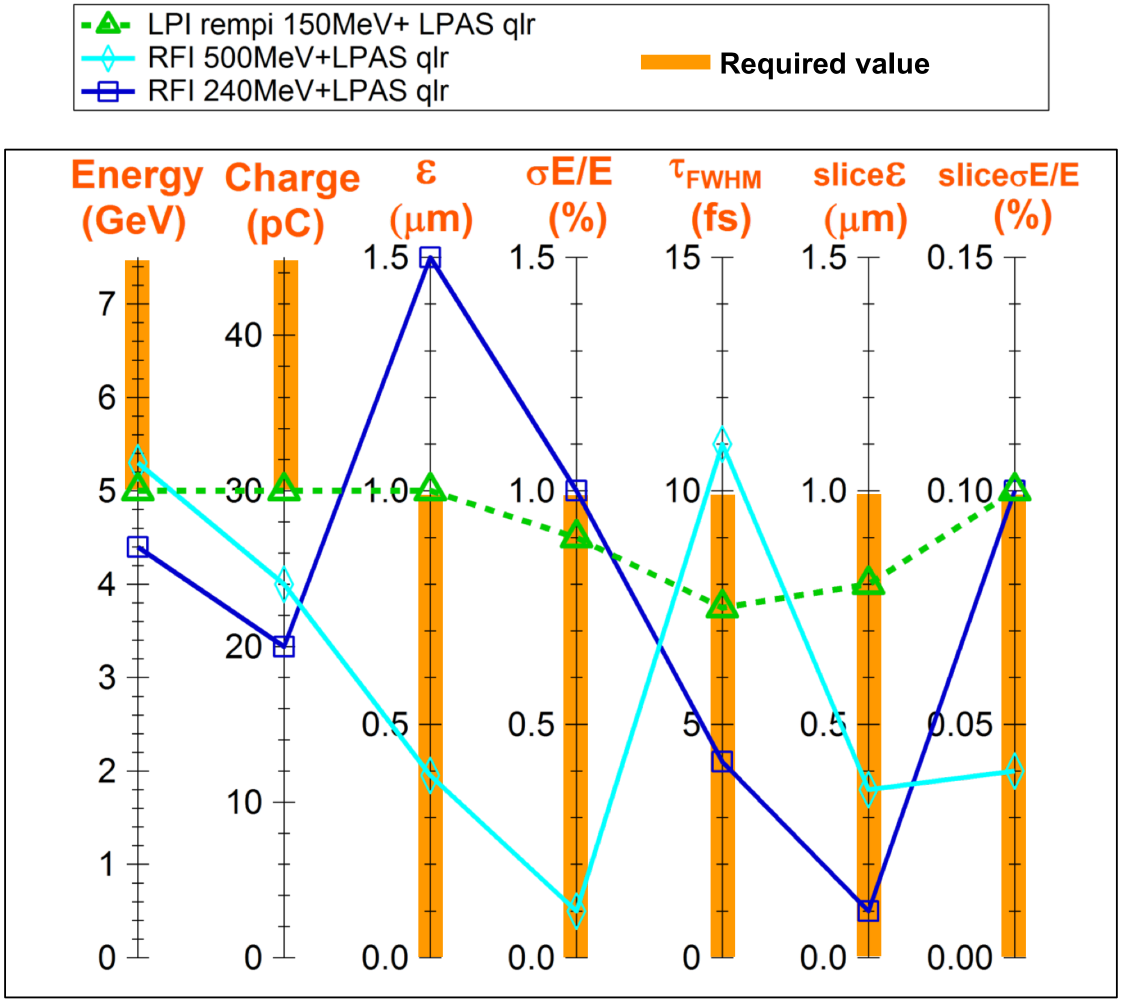
Configurations closest to the requirements



Beam parameters obtained at 5 GeV

1-LPAS configurations closest to the requirements

quasilinear acceleration with external injection



Four experts
Four institutes

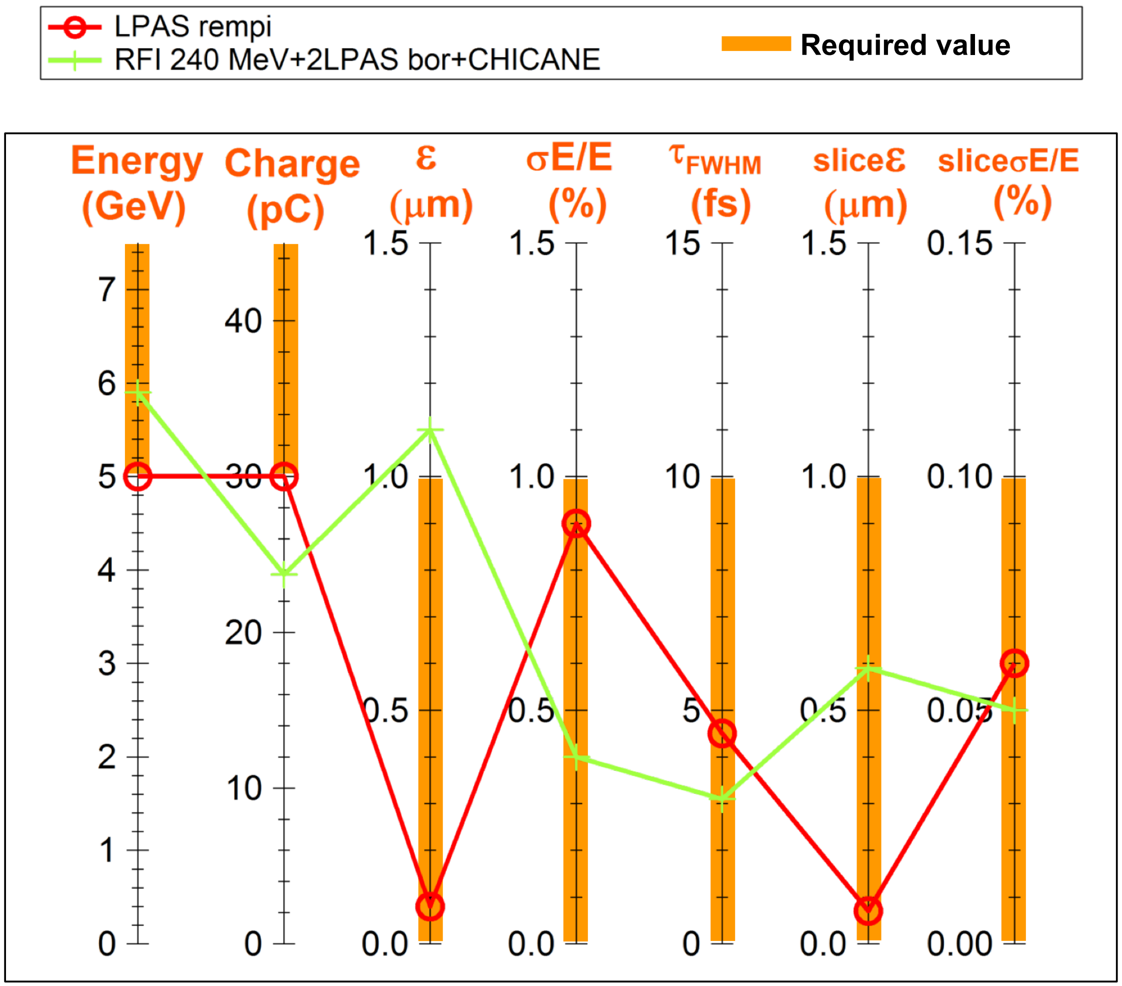
Three codes used:
- **Warp 3D**
- **QFluid ~3D**
- **FBPIC 3D**

Four beam inputs:
- **BiGaussian**
- **LPI 150 MeV**
- **RFI 240 MeV**
- **RFI 540 MeV**

Close parameters of laser & plasma
⇒
Close results

Very robust configuration !!!

Beam parameters obtained at 5 GeV



LPAS ReMPI: very low emittance

RFI 240 MeV+2LPAS bor+CHICANE: very low energy spread

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Decoupling injection and acceleration

Accelerator: stability, reliability, reproducibility ← simplicity!
High energy, high charge and high quality ← sophistication!

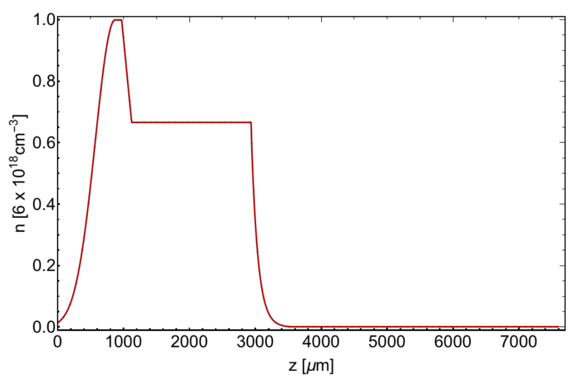
TWO STAGES: INJECTION + ACCELERATION

high charge
high quality

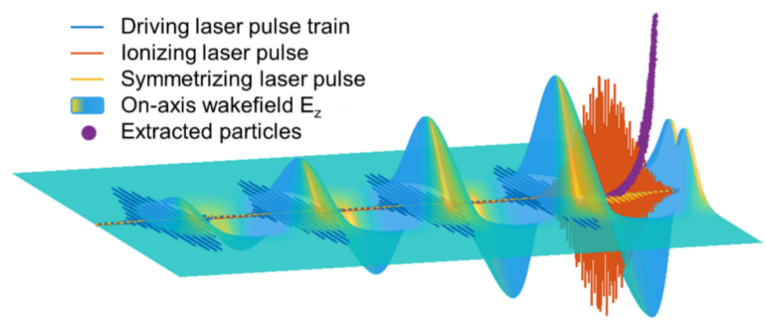
high energy

also FOR THE INJECTOR ITSELF: uncouple injection and acceleration

150 MeV



Downramp injection



ReMPI

Decoupling injection and acceleration

One stage, ReMPI

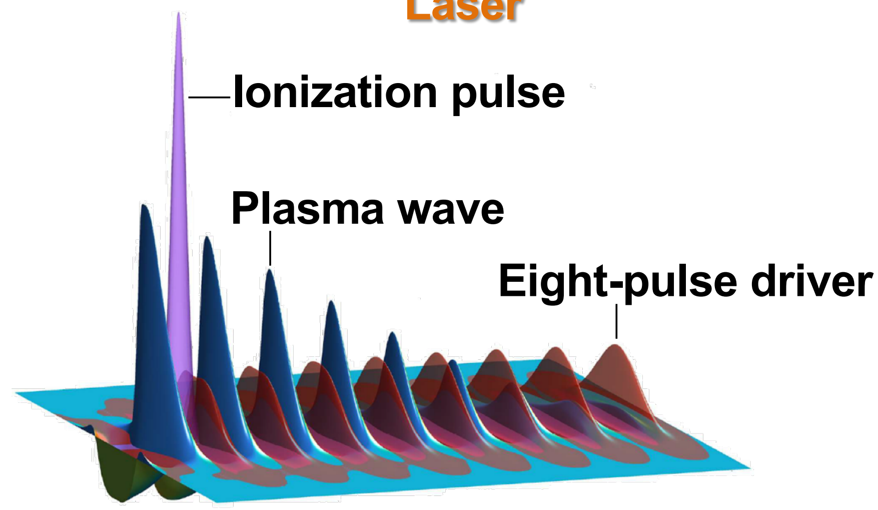
Plasma

n_e=2.1 10^{17} cm^{-3}

Injection stage
He+Ar^{8+} (50%)
Gas cell

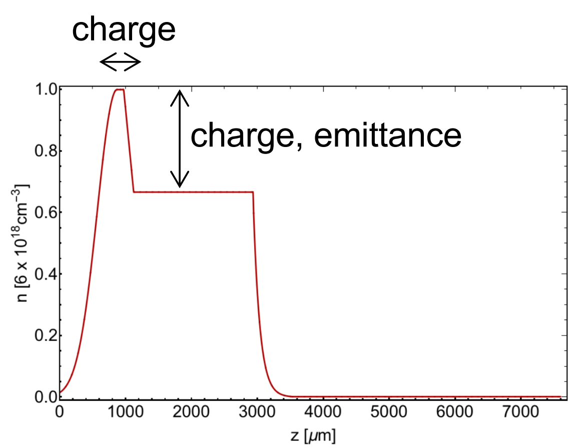
Acceleration stage
He, parabolic profile
Capillary tube

Laser



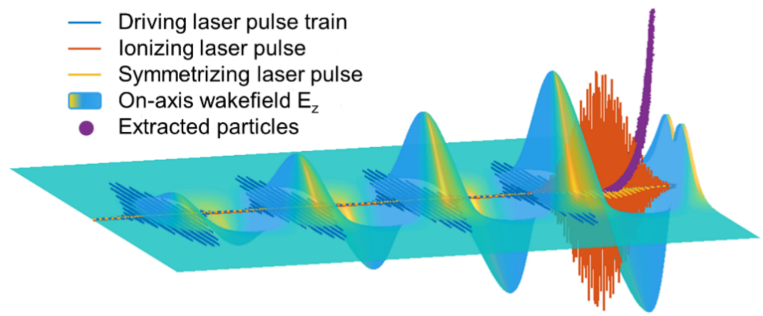
High beam quality and high charge

For injection: higher charge ⇒ higher emittance



Downramp injection

Judicious choice of
- ramp sharpness
- density jump



ReMPI

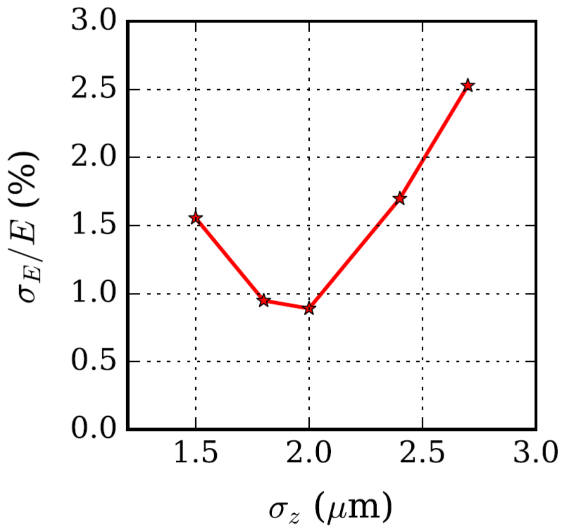
Judicious choice of
- ionization pulse strength & size
- ionization potential of the gas

charge
emittance

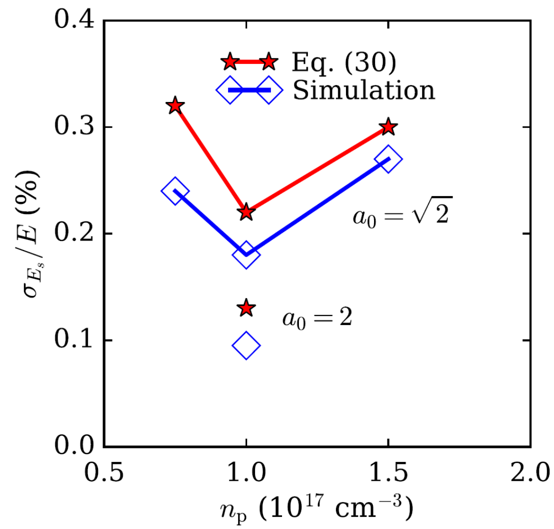
High beam quality and high charge

For acceleration: minimize energy spread in the presence of high charge

In the presence of significant beam loading



Minimizing energy spread by optimizing the bunch length



Minimizing slice energy spread by optimizing jointly the plasma density & the laser strength

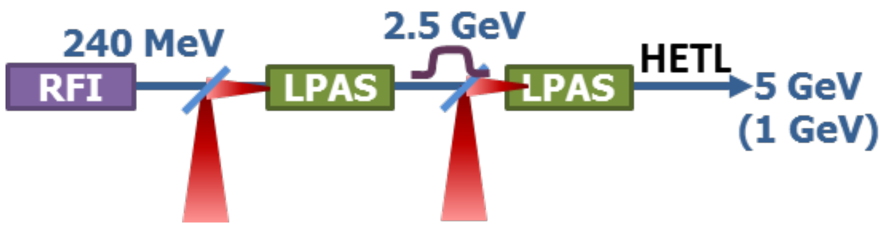
Wakefield & bunch length — **energy spread** — Beamloading field & bunch radius ← Bunch charge

$\frac{\sigma_{E,s}}{E_0}$ — Beamloading field ↗ $\sqrt{n_p}$ and ↘ a_0 ← Bunch charge; — Av. energy gain by wakefield ↘n_p

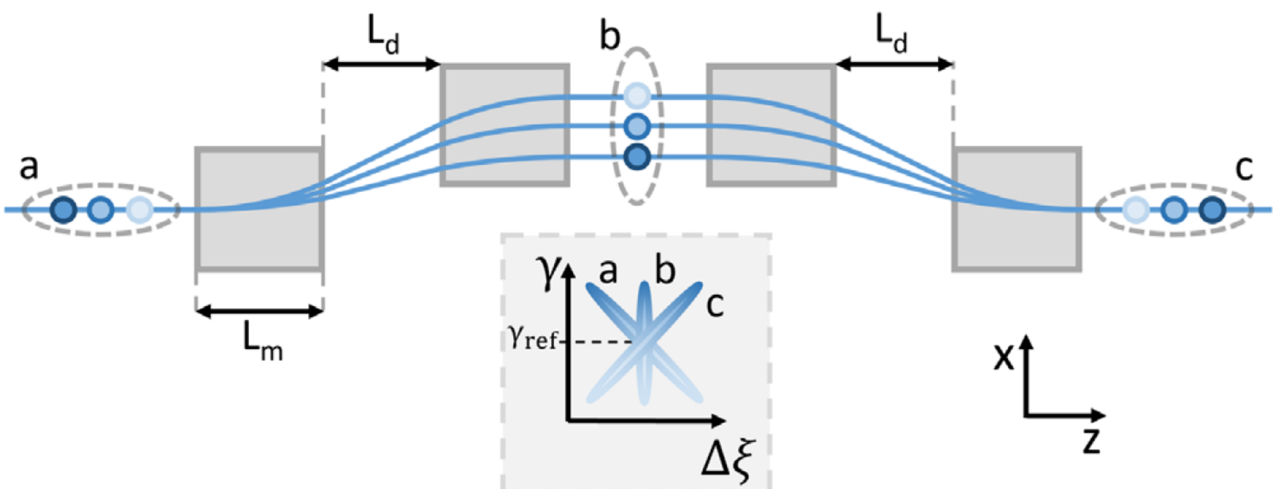
High beam quality and high charge

For acceleration: minimize energy spread in the presence of high charge

Two plasma stages with magnetic chicane



Energy dechirping



1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. **Optimization of beam extraction and transport**

4. Estimation of sensitivity to errors

5. Specification for plasma and laser systems

The key issue: minimize emittance growth

It is well known: beam extraction and transport → important emittance growth
Floettmann, PRAB 2003; Dornmair, Floettmann & Maier, PRSTAB 2015, …
Xu et al. PRL 2016 …

But: only solutions of downramp without space charge nor beam loading

And: three pending questions without explicit answer

1- Which emittance? (Phase or Trace emittance?)

2- In which circumstances? (Drift or Focusing element?)

3- Which parameters govern the emittance growth?

→ **Answer ≡ Know how to mitigate emittance growth**

The two emittances

Trace Emittance

$$\varepsilon_{tr} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

$$\varepsilon_{tr,n} = \beta_r \gamma_r \varepsilon_{tr}$$

RMS beam size, divergence, Emittance, Twiss parameters

Phase Emittance

$$\varepsilon_{ph} = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2}$$

$$\varepsilon_{ph,n} = \frac{\epsilon_{ph}}{m_0 c}$$

x, px **are conjugate variables**

After some algebra:

$$\varepsilon_{ph}^2 = \varepsilon_{tr}^2 \left(\overline{p_z^2} + \alpha^2 \sigma_p^2 \right)$$

$$\varepsilon_{ph,n} = \varepsilon_{tr,n} \quad when\ \alpha = 0.$$

Should minimize growth of both emittances

Emittance evolution through a drift

Through a drift of length l, the coordinates change as:

$$\begin{cases} x = x_0 + x_0' l \\ x' = x_0' \end{cases}$$

$$\begin{cases} \varepsilon_{tr}^2 - \varepsilon_{tr0}^2 = 0. \\ \varepsilon_{ph}^2 - \varepsilon_{ph0}^2 = \varepsilon_{tr0}^2 \sigma_p^2 \gamma_0 l (\gamma_0 l - 2\alpha_0) \end{cases}$$

Role of the acceleration plasma

Migliorati et al. PRSTAB 2013; Sciscio et al., JAP 2016; etc.:

As ε_{tr0}^2 and σ_p^2 are big in plasma acceleration, big emittance growth is unavoidable

NO! Minimizing l or/and minimizing γ_0 can help preserving emittance!

Role of the transfer line

Role of the plasma downramp

Emittance evolution through a thin lens

Through a thin lens of focusing gradient K, the coordinates change as:

$$\begin{cases} x = x_0 \\ x' = Kx_0 + x'_0 \end{cases}$$

$$\Rightarrow \begin{cases} \dfrac{\varepsilon_{tr}^2 - \varepsilon_{tr0}^2}{\varepsilon_{tr0}^2} = \beta_0^2 K^2 \left(\dfrac{\sigma_p}{p_0}\right)^2 \\ \varepsilon_{ph}^2 - \varepsilon_{ph0}^2 = 0 \end{cases}$$

Role of the acceleration plasma

Emittance growth is minimized when:

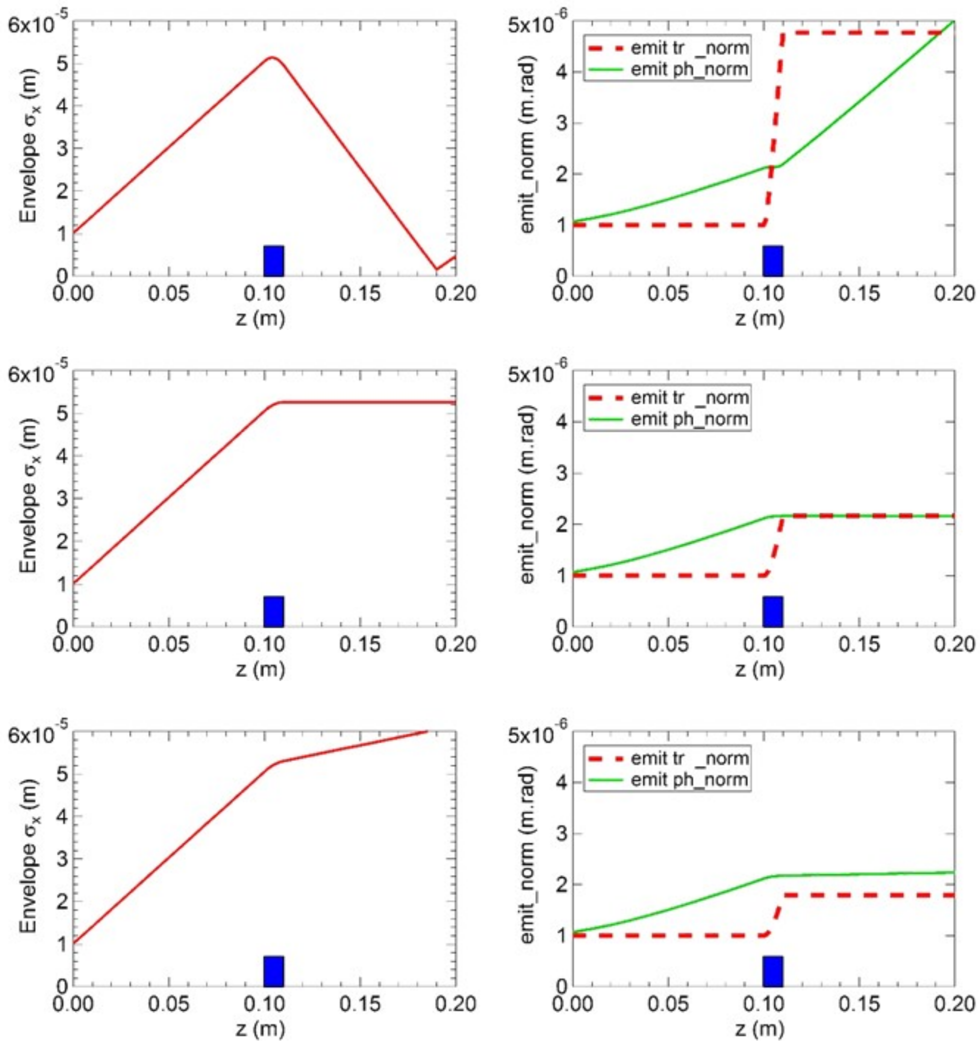
- Minimizing $\boldsymbol{\beta_0} \equiv$ Minimizing $\boldsymbol{\gamma_0}$ in the upstream drift

Role of the plasma downramp

- Minimizing $\boldsymbol{K_0}$

Role of the transfer line

Particle tracking



TraceWin code (CEA)

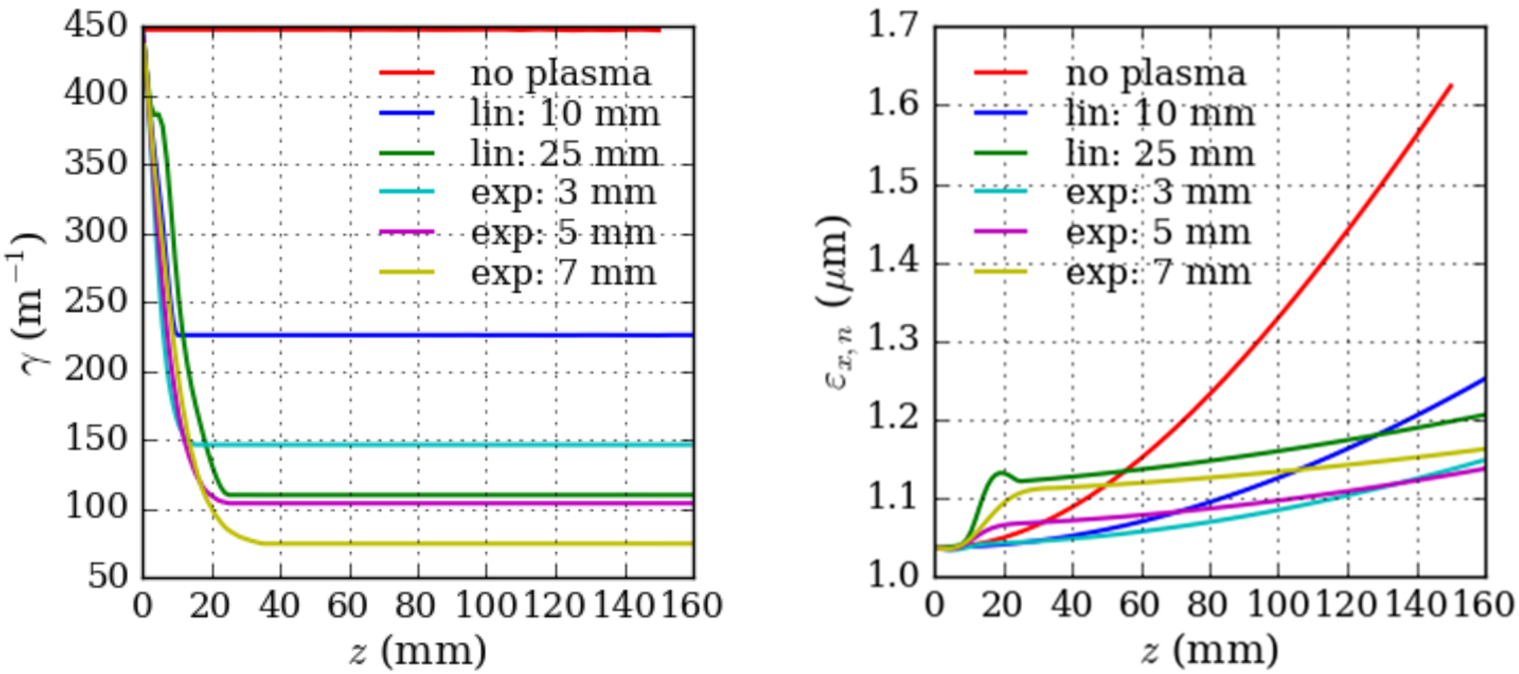
The three key roles

In the plasma: minimize Emittance and Energy Spread
(as done previously)

In the downramp: minimize γ
by tuning the ramp length (whatever its shape)

In the transfer line: minimize the first drift and use the smoothest focalization
→ use as few quadrupoles as possible (~6)

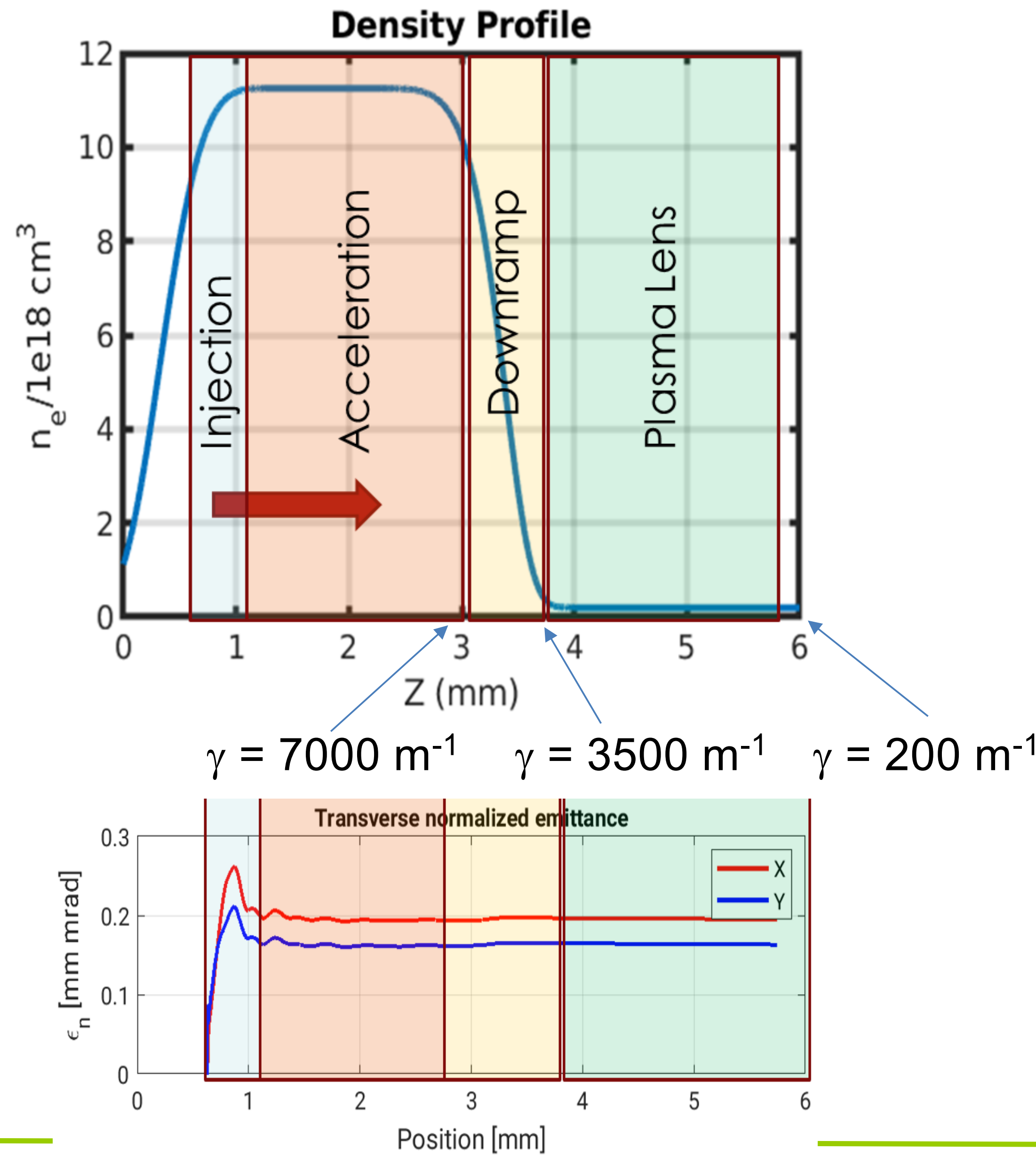
Plasma exit 5 GeV



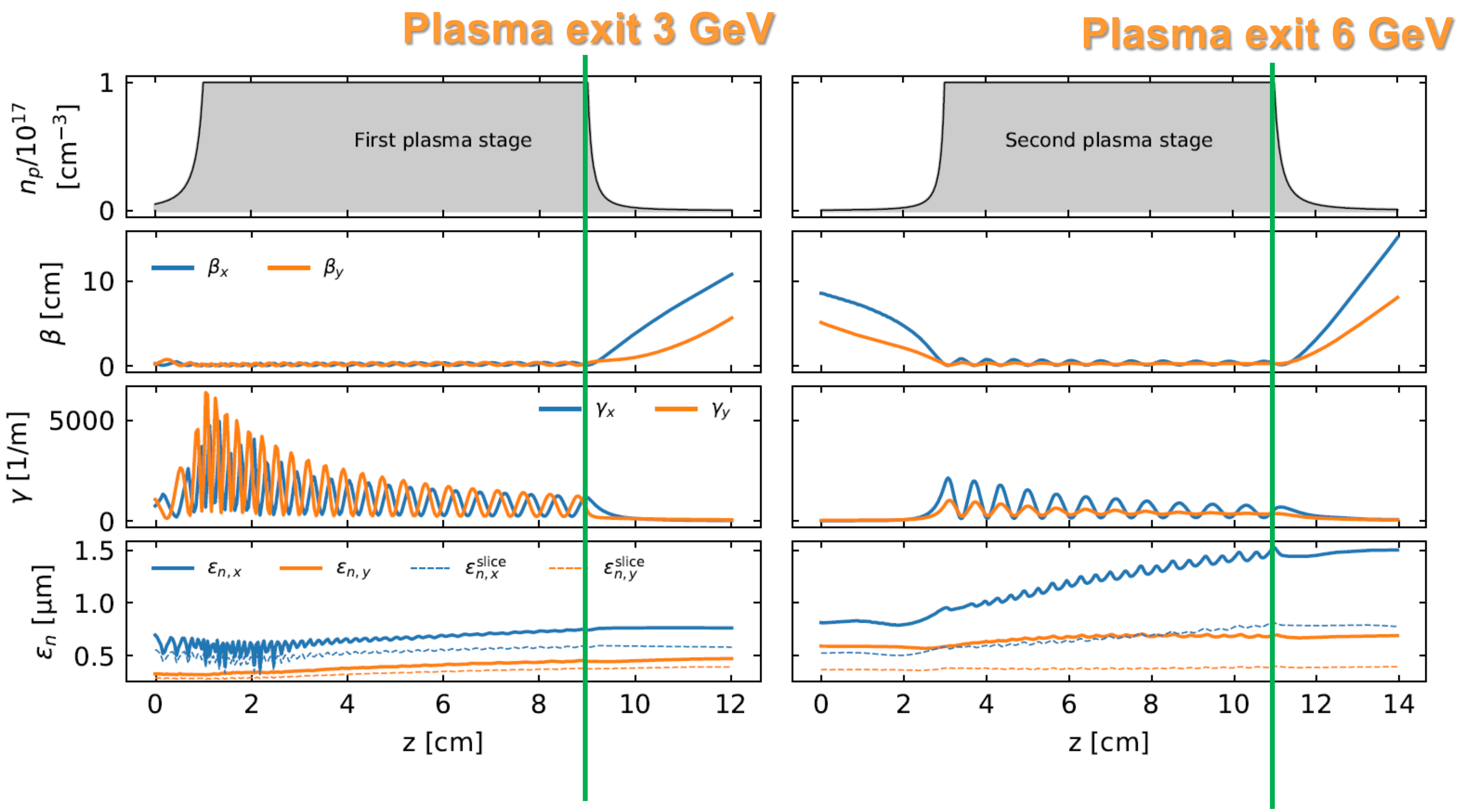
Tuning the ramp length (whatever its shape)
⇒ Minimizing γ_0 ⇒ Minimizing emittance growth

Plasma downramp

Plasma exit 150 MeV



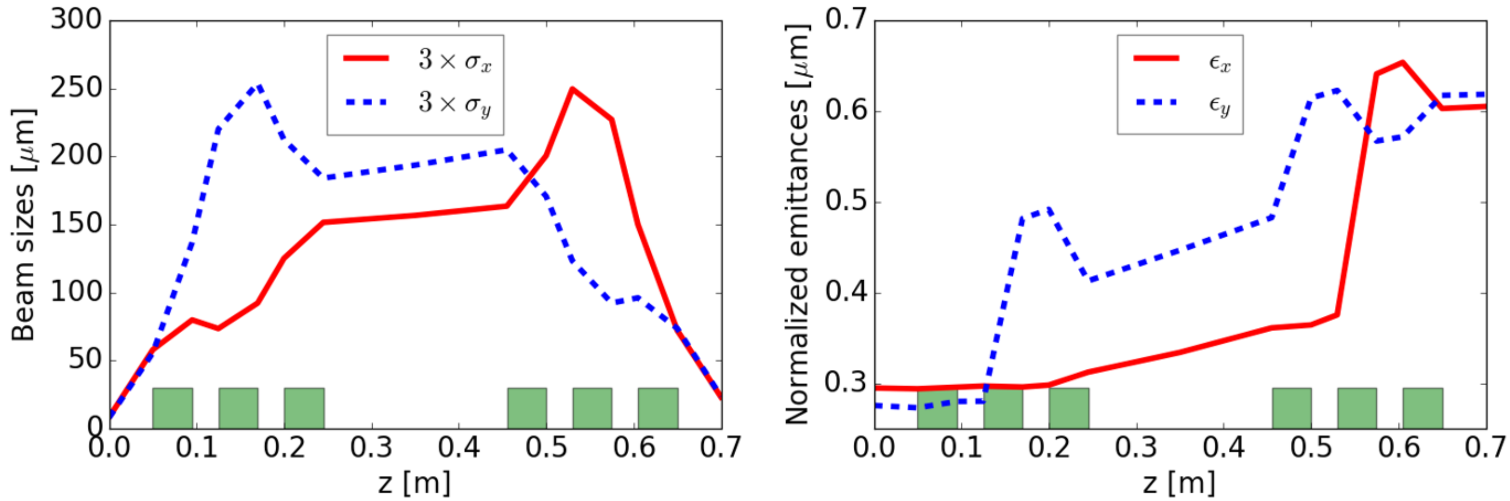
Plasma downramp



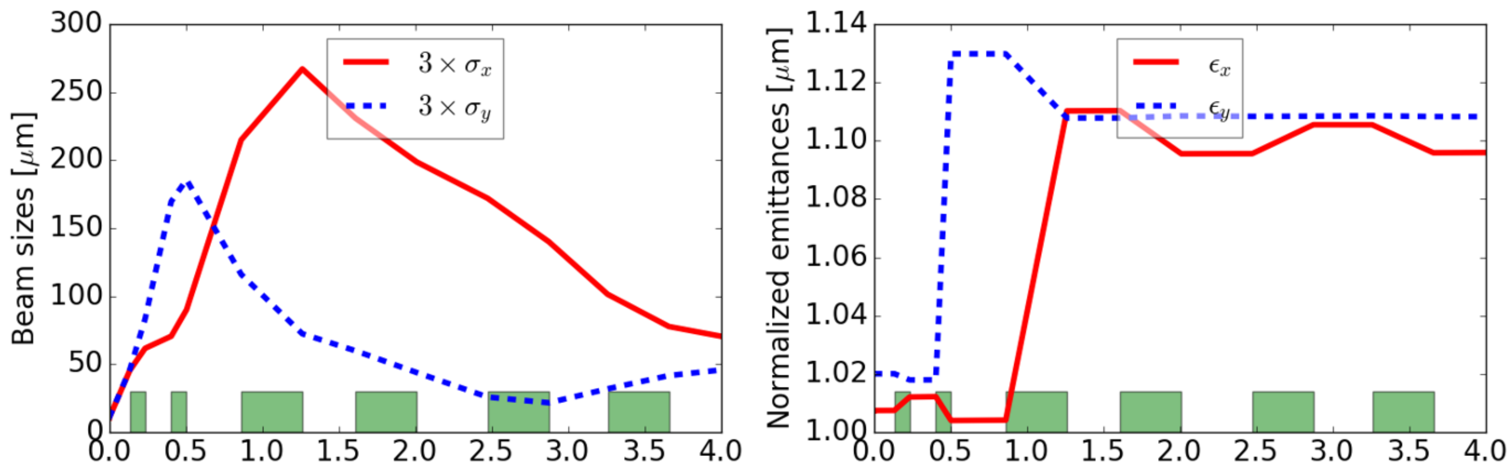
Transfer line

Rule: smoothest focusing → number of quadrupoles= number of constraints (~6)

LETL 150 MeV



HETL 5 GeV



Total emittance growth from LPAS injection to end user: 22%

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Sensitivity to errors

Heavy simulations!!! To be completed
Errors ≡ Jitters
The most critical points are:

In the plasma stages: For laser and electron beams,
- Position vibrations should be a small fraction of their size
  → consistency of error simulations
  → stability of the selected schemes, no surprising error amplification
- Departure to cylindrical symmetry should be very tightly controlled
  Strong effects on final emittance and slice energy spread

In the transport lines:
Magnet position vibrations in the capture section should be < μm
Strong effects on final electron beam position
→ vibration dampers to mitigate low-frequency vibrations
→ fast feedback to compensate high-frequency vibrations

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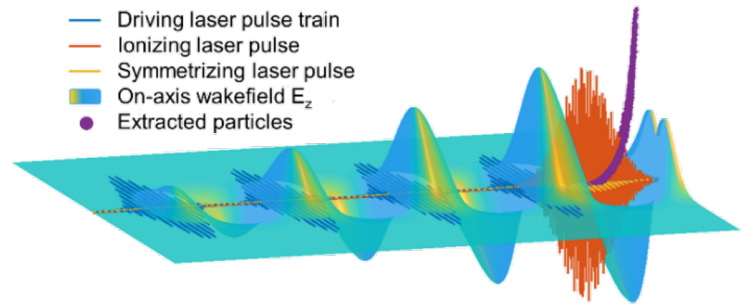
Specifications for laser & plasma

150 MeV "ReMPI"

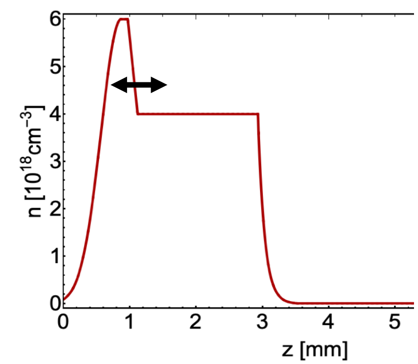
Driving laser: decomposed in 4 subpulses, delay 160 fs
120 TW, 4 J, w_0 = 30 μm (a_0 = 1, τ_{FWHM} = 30 fs)
Ionizing laser: 3rd harmonic
1.0 TW, 0.07 J, w_0 = 3.8 μm (a_0 = 0.53, τ_{FWHM} = 45 fs)
Symmetrization laser: 3rd harmonic, delay 40 fs
0.7 TW, 0.02 J, w_0 = 11 μm (a_0 = 0.14, τ_{FWHM} = 25 fs)

Plasma: radially uniform, length 3.5 mm + 1 mm ramp
N preionized up to 5^+, density n_0 = 5 10^{17} cm^{-3}
+ 3 mm passive plasma lens, n_0 = 1.4 10^{16} cm^{-3}



150 MeV "Downramp Injection"

Laser: 35 TW, 1.05 J, w_0 = 18 μm (a_0= 1.8, τ_{FWHM} = 30 fs)
(a_0 will be x 2 by self focusing)
Plasma: radially uniform, ~3.5 mm long
~1 mm upramp, ~0.1 mmm plateau at n_0 = 6 10^{18} cm^{-3}
~0.15 mm downramp, 1.8 mm accelerating plateau at n_0 = 4 10^{18} cm^{-3}
Exit ramp exponential L_{exp}=0.1 mm
+ passive plasma lens ~4mm at n_0 = 1 10^{16} cm^{-3}



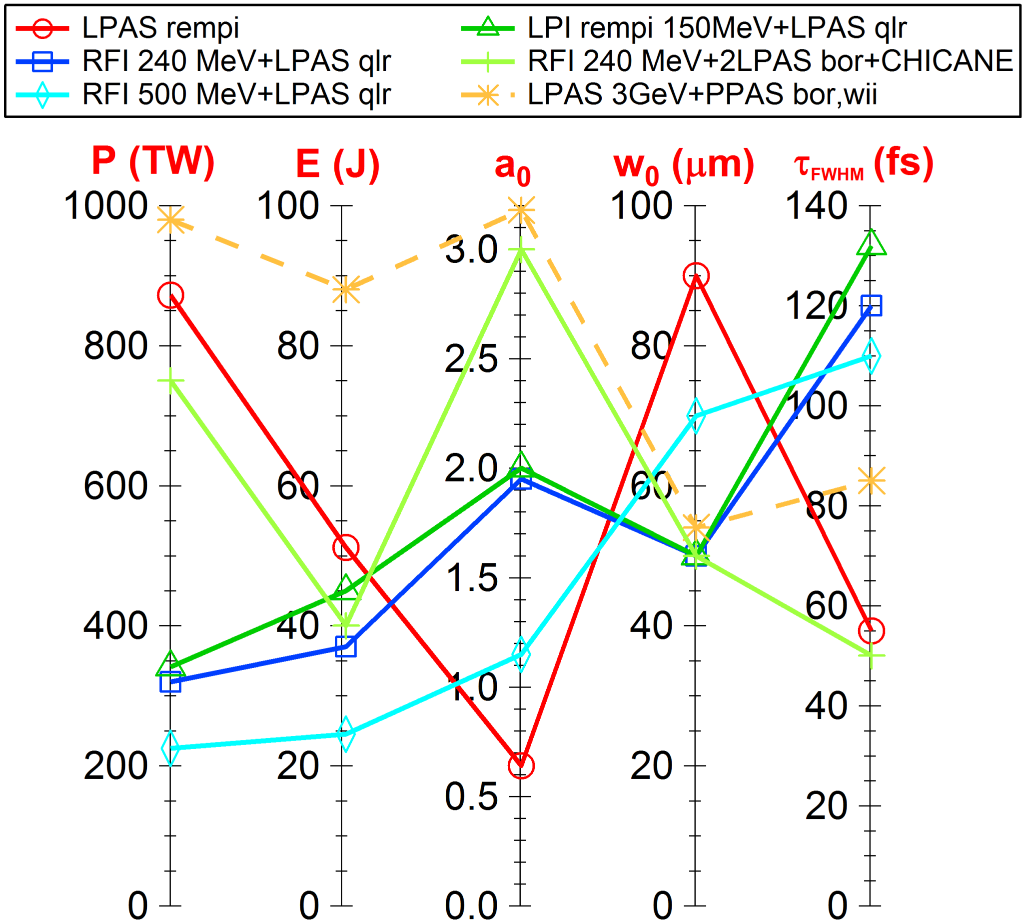
5 GeV Quasilinear acceleration with external injection

Laser: P = 400 TW, E = 60 J, w_0 = 45 μm (a_0 = 2.42, τ_{FWHM} = 141 fs)
Bi gaussian
Plasma: parabolic in r, $\Delta n/n_c$ = 1 to 0.3
unniform in z, 30 to 50 cm long, n_0 = 1 to 2 10^{17} cm^{-3}
entrance and exit ramps ~2 cm

Specifications for plasma:
n_0 = ~10^{17} cm^{-3}, parabolic in r
With tunable density, length
tunable radial profile
tunable ramp lengths

Specifications for laser & plasma

Laser parameters for 5 GeV



Bi-Gaussian pulse
λ = 800 nm

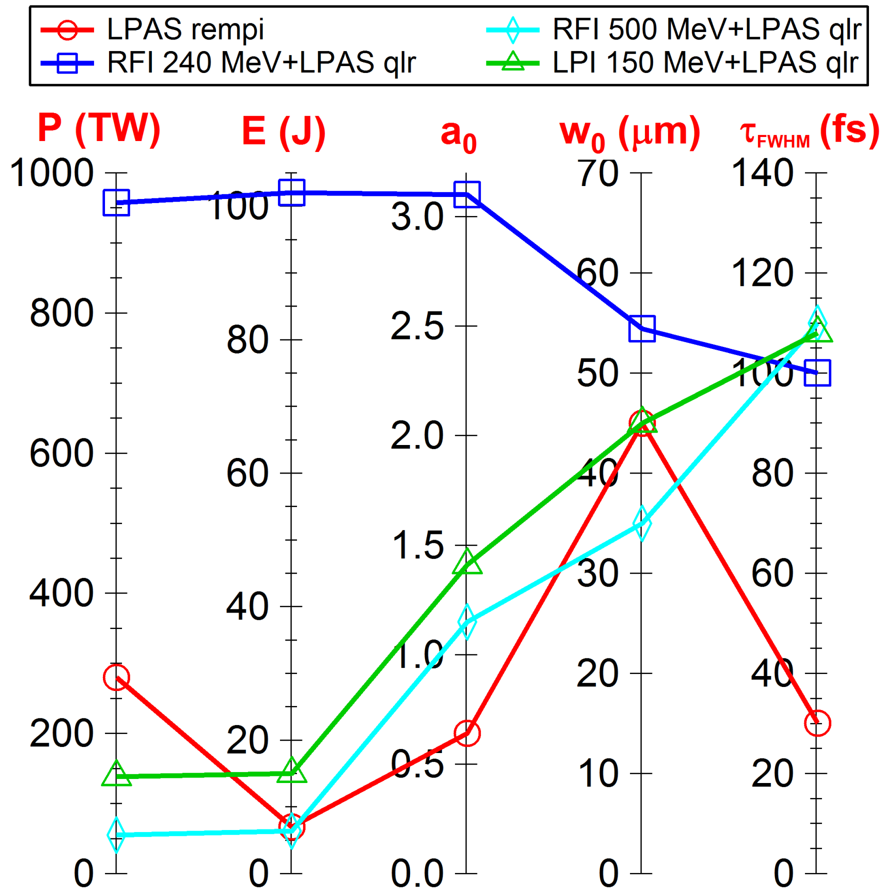
LPAS rempi:
driver pulse decomposed into 8 sub-pulses
ionization pulse at 4th harmonic

RFI 240 MeV+2LPAS bot+CHICANE:
two identical driver pulses for the two stages

➡ Required laser parameters: for qlr, P = 400 TW, E = 60 J, w_0 = 45 μm (a_0 = 2.42, τ_{FWHM} = 141 fs)
others, P = 1000 TW

Specifications for laser & plasma

Laser parameters for 1 GeV



Bi-Gaussian pulse
λ = 800 nm

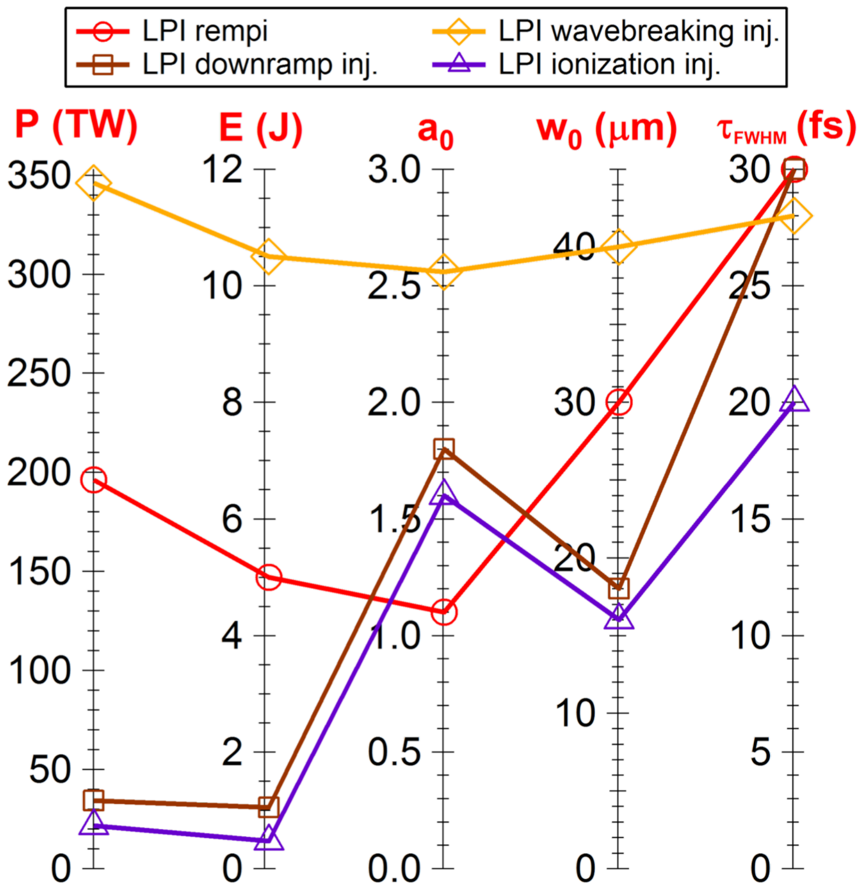
LPAS rempi:
driver pulse decomposed into 8 sub-pulses
ionization pulse at 4th harmonic

RFI 500 MeV+LPAS:
cosine squared in longitudinal

➡ Required laser parameters: P = 200 TW, E = 30 J, w_0 = 30 μm (a_0 = 2.57, τ_{FWHM} = 141 fs)

Spécifications for laser & plasma

Laser parameters for 150 MeV



Bi-Gaussian pulse
λ = 800 nm

LPI rempi:
driver pulse decomposed into 4 sub-pulses
ionization pulse at 3rd harmonic

Required laser parameters: P = 50 TW, E = 1.5 J, w_0 = 20 μm (a_0 = 1.93, τ_{FWHM} = 29 fs)
P = 250 TW, E = 10 J, w_0 = 30 μm (a_0 = 2.87, τ_{FWHM} = 38 fs)

Summary

Tremendous simulations and optimizations have been performed by many contributors

→ Many results obtained on different injection/acceleration schemes and techniques

→ First down selection performed for S2E simulations

→ Issues of emittance growth addressed and solved

→ Thorough S2E simulations done

→ Beam parameters at user's doorstep very close to all the requirements

A certain level of sophistication is necessary

Solutions do exist, at least one configuration is robust

Other schemes or techniques remain promising
Further progress is still possible

The message

The EuPRAXIA project

has been studied as for a

regular ACCELERATOR project

Beam physics