Simulations for EuPRAXIA Accelerator Design

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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 1-5 GeV plasma-based electron <u>accelerator</u>
  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 !

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

OBJECTIVE:

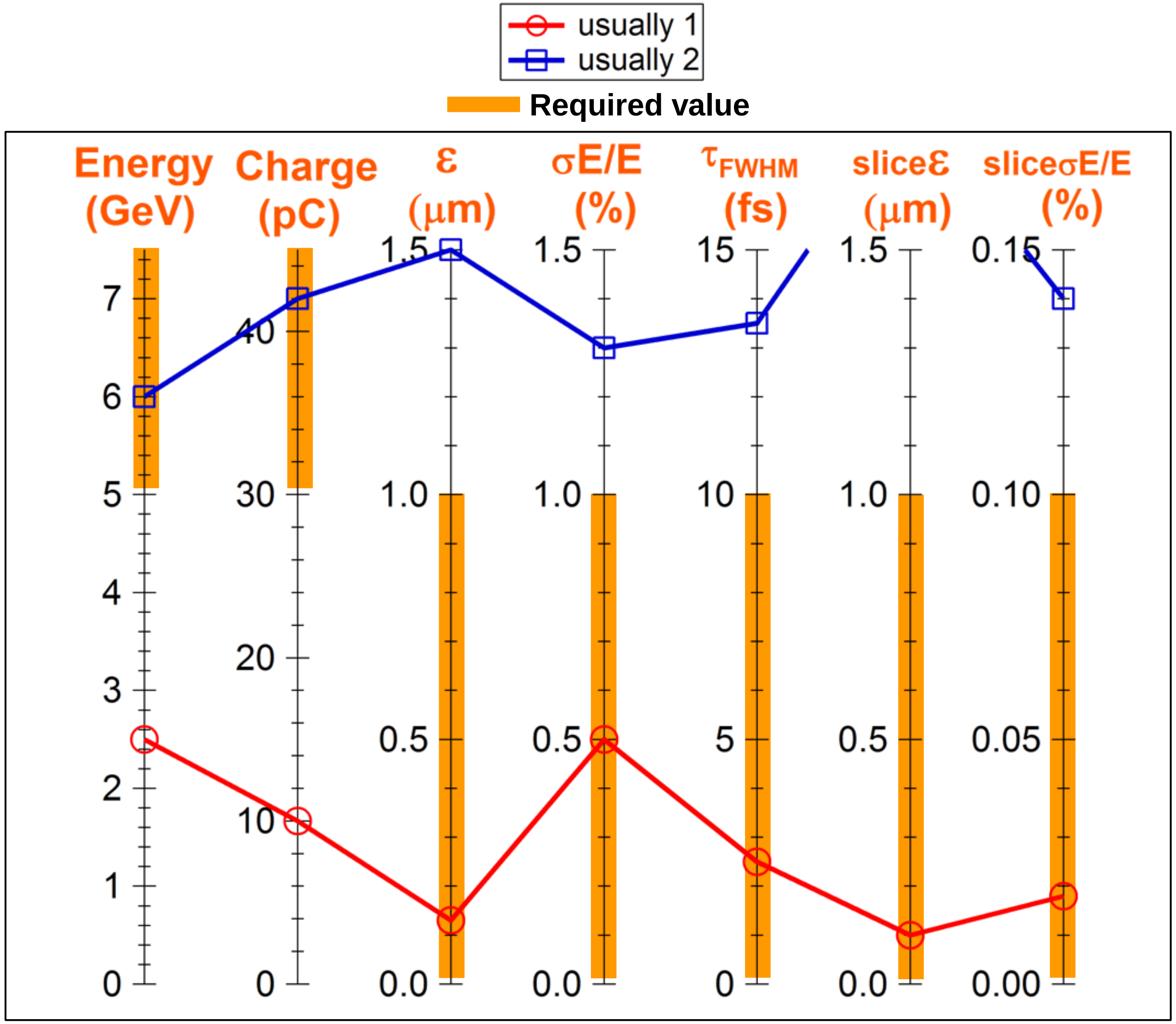
- Providing beam at 5 GeV meeting 'perfectly' FEL and HOPA requirements

- Providing 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! (Accelerator exit)

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

1. Definition of the desired beam parameters (TLR)

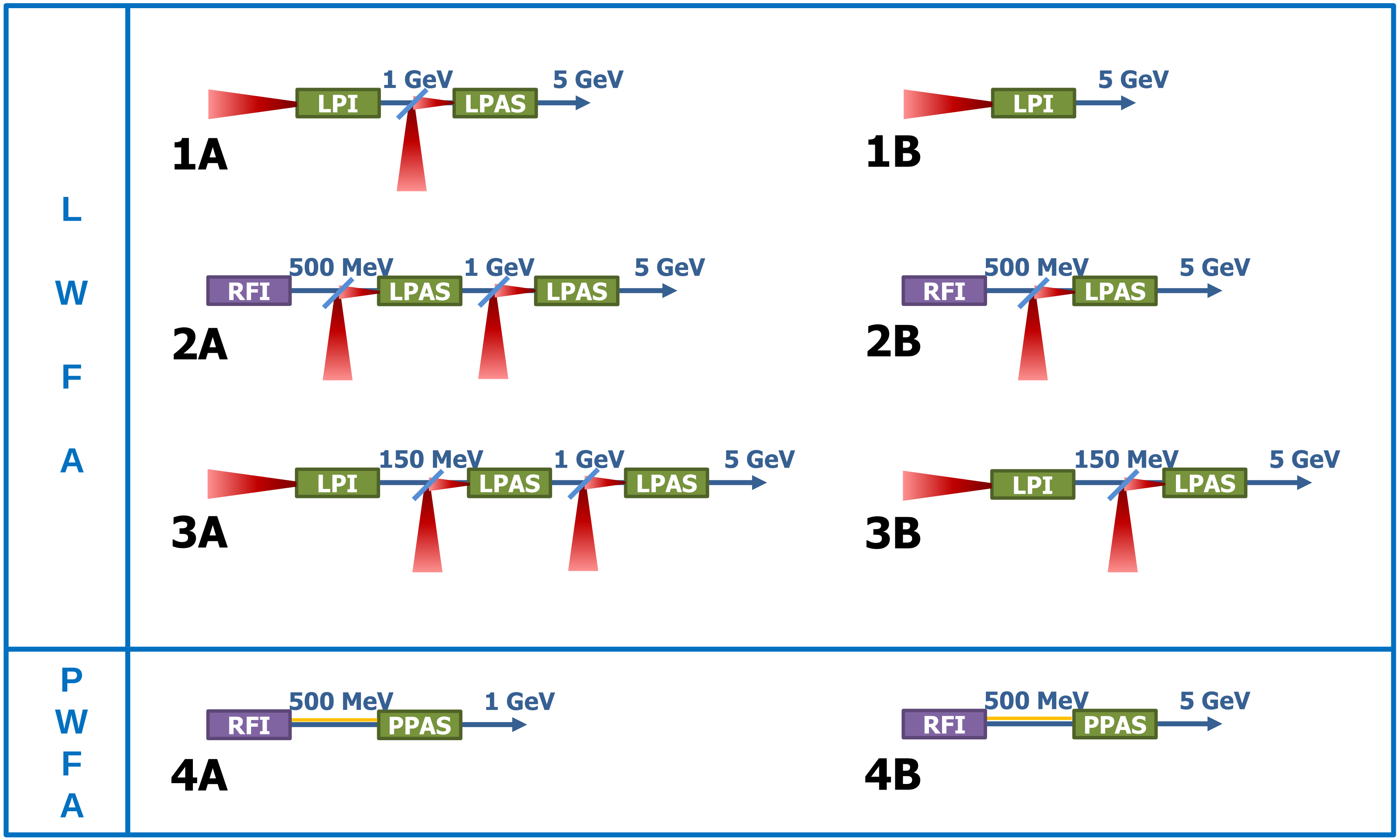
2. Large exploration (simulations) of inject./accelerat. configurations

3. Selection of the appropriate configurations

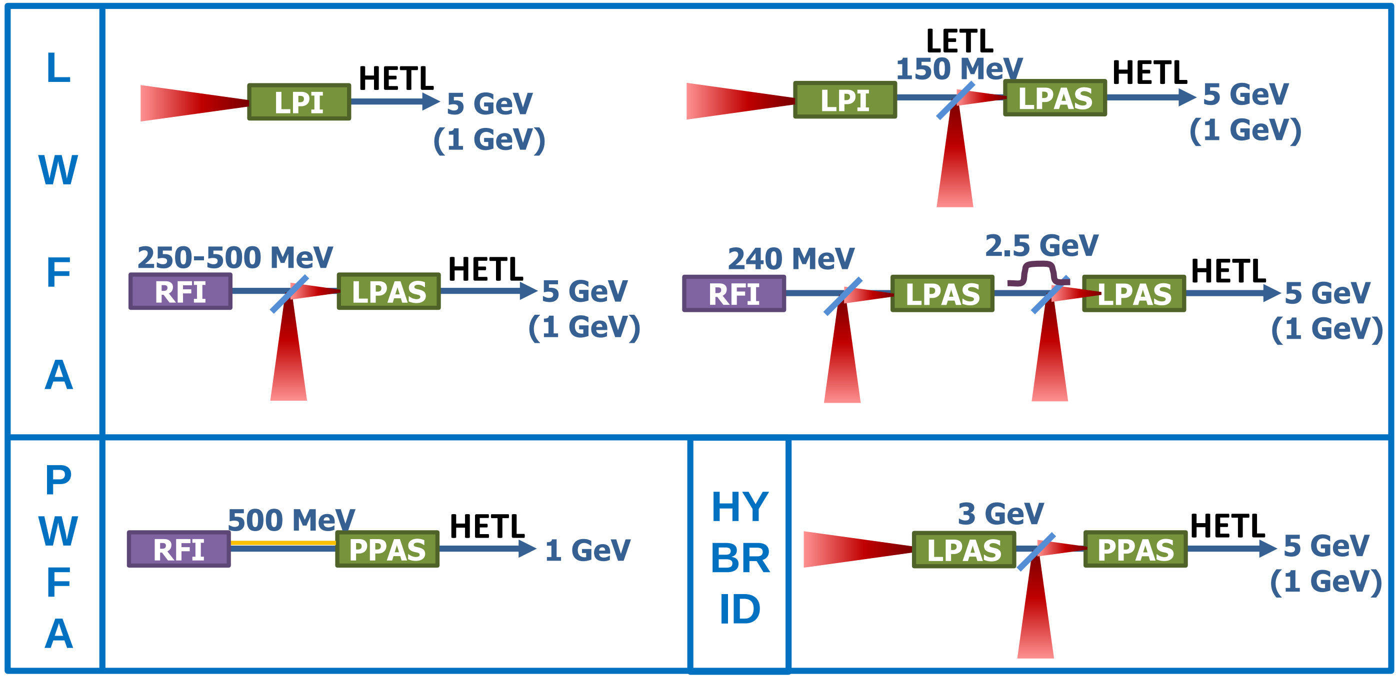
4. Determination of specifications for the laser and plasma systems

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

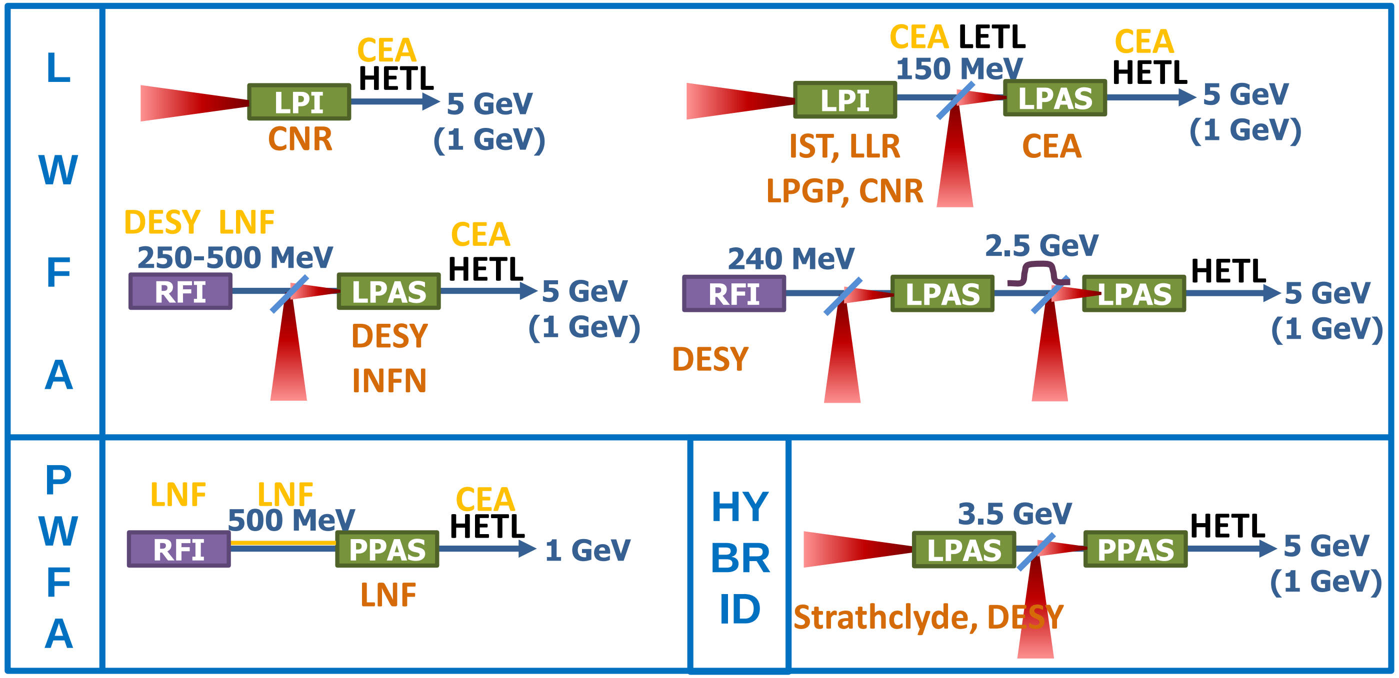
Inj. / Accel. schemes considered



Inj. / Accel. schemes studied



Inj. / Accel. schemes studied



11 European institutes
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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 quasi-linear regime Downramp injection and blow-out regime Resonant Multiple Ionization Injection (ReMPI)
LPAS 5 GeV	Quasi-linear regime, 1 LPAS Blow-out regime, 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 quasi-linear regime	Warp
	Downramp injection and blow-out regime	OSIRIS
	Resonant Multiple Ionization Injection (ReMPI)	ALaDYN, QFluid
LPAS 5 GeV	Quasi-linear regime, 1 LPAS	FBPIC, QFluid, Warp
	Blow-out regime, 2 LPAS + chicane	FBPIC, ASTRA, CSRtrack
PPAS 1 GeV	Weakly-nonlinear regime	Architect
LPAS-PPAS	Trojan Horse Injection and blow-out regime	VSim
	Wakefield Induce Ionization and blow-out regime	OSIRIS

Published results

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).

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).

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).

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).

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).

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).

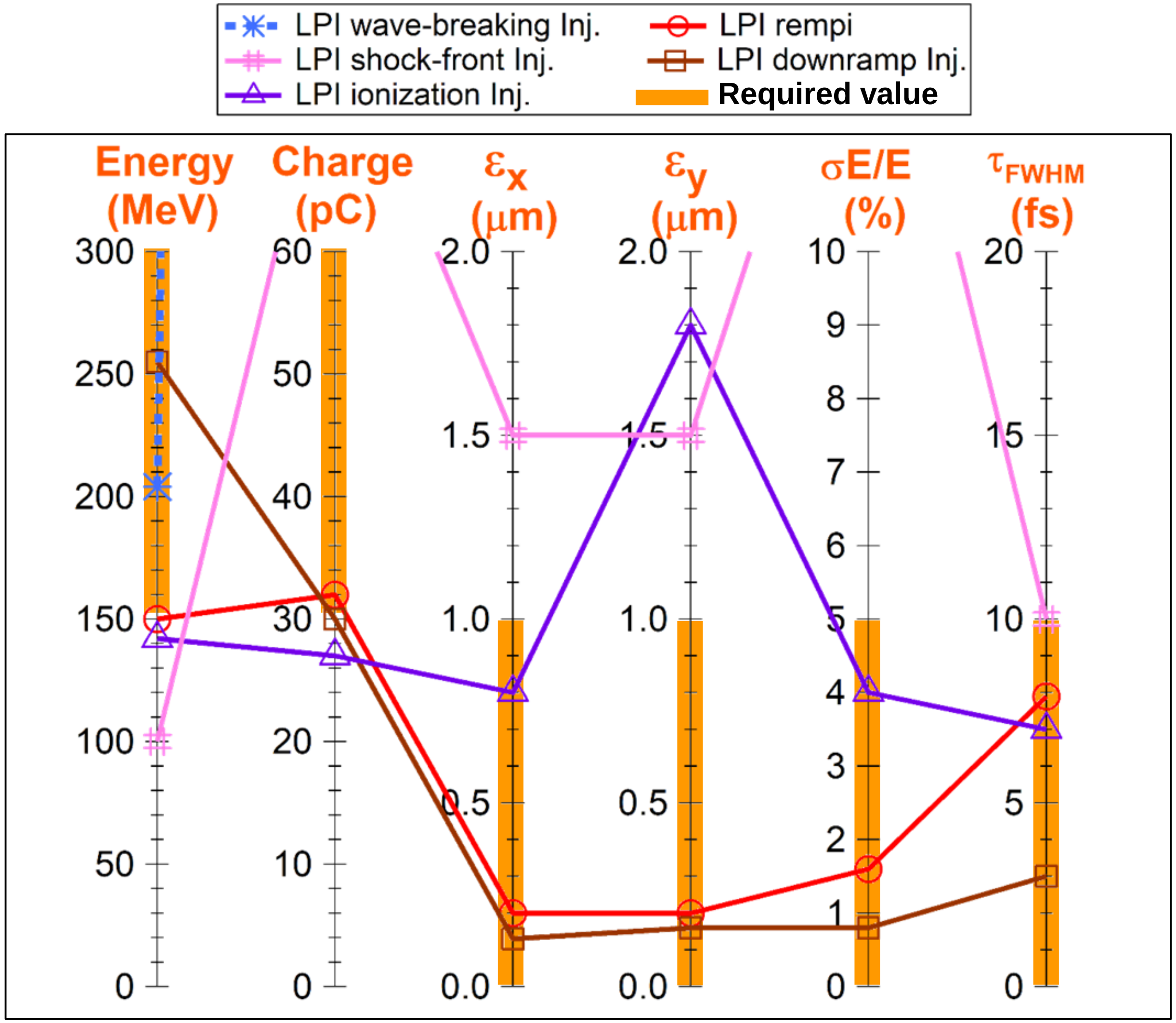
Optimization of laser-plasma injector via beam loading effects using ionization-induced injection, P. Lee, G. Maynard, T. L. Audet, B. Cros, R. Lehe and J.-L. Vay, Phys. Rev. Accel. Beams, 21, 052802 (2018).

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).

Etc…………………………..

Beam parameters obtained at 150 MeV

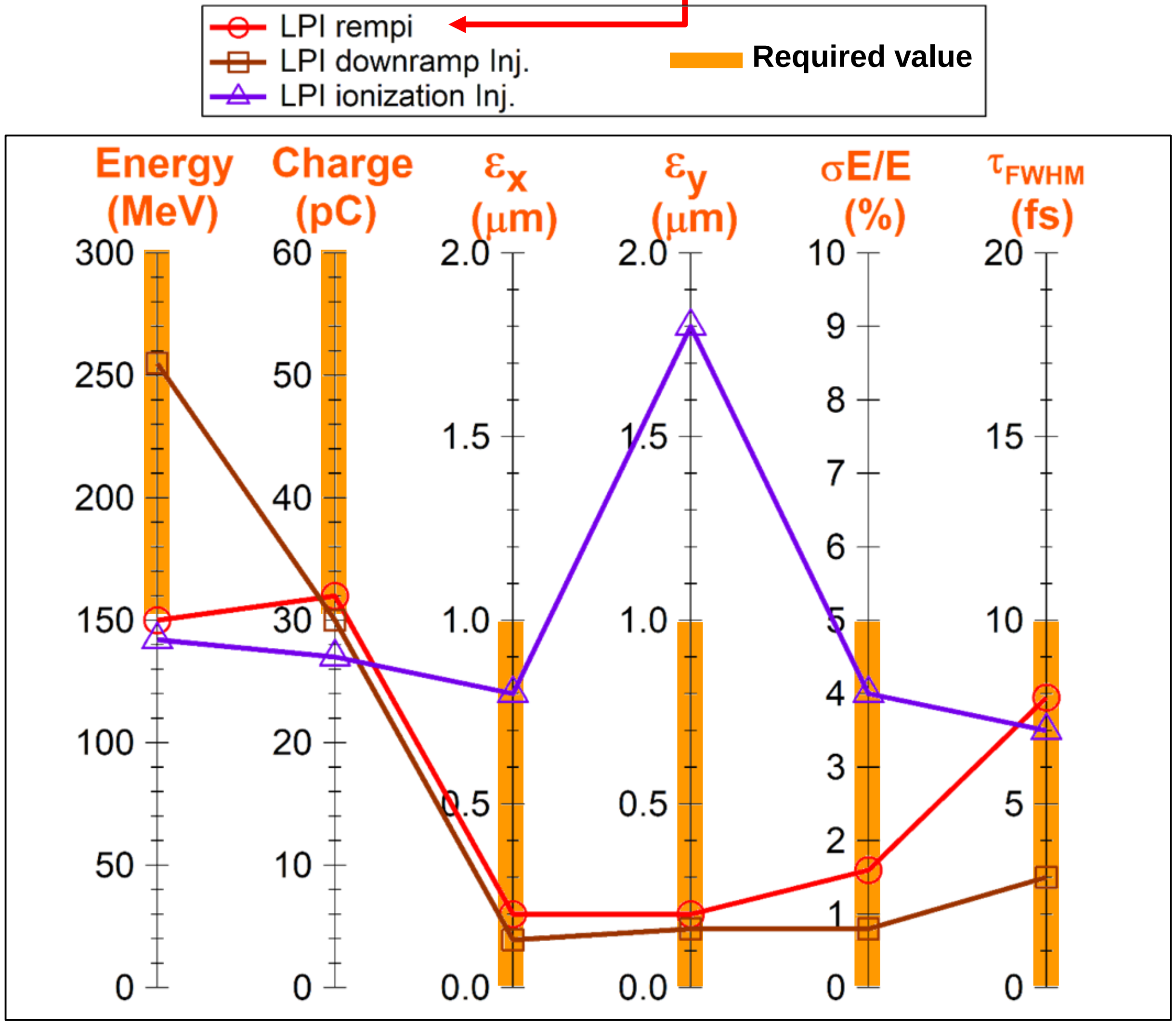
All the configurations



Beam parameters obtained at 150 MeV

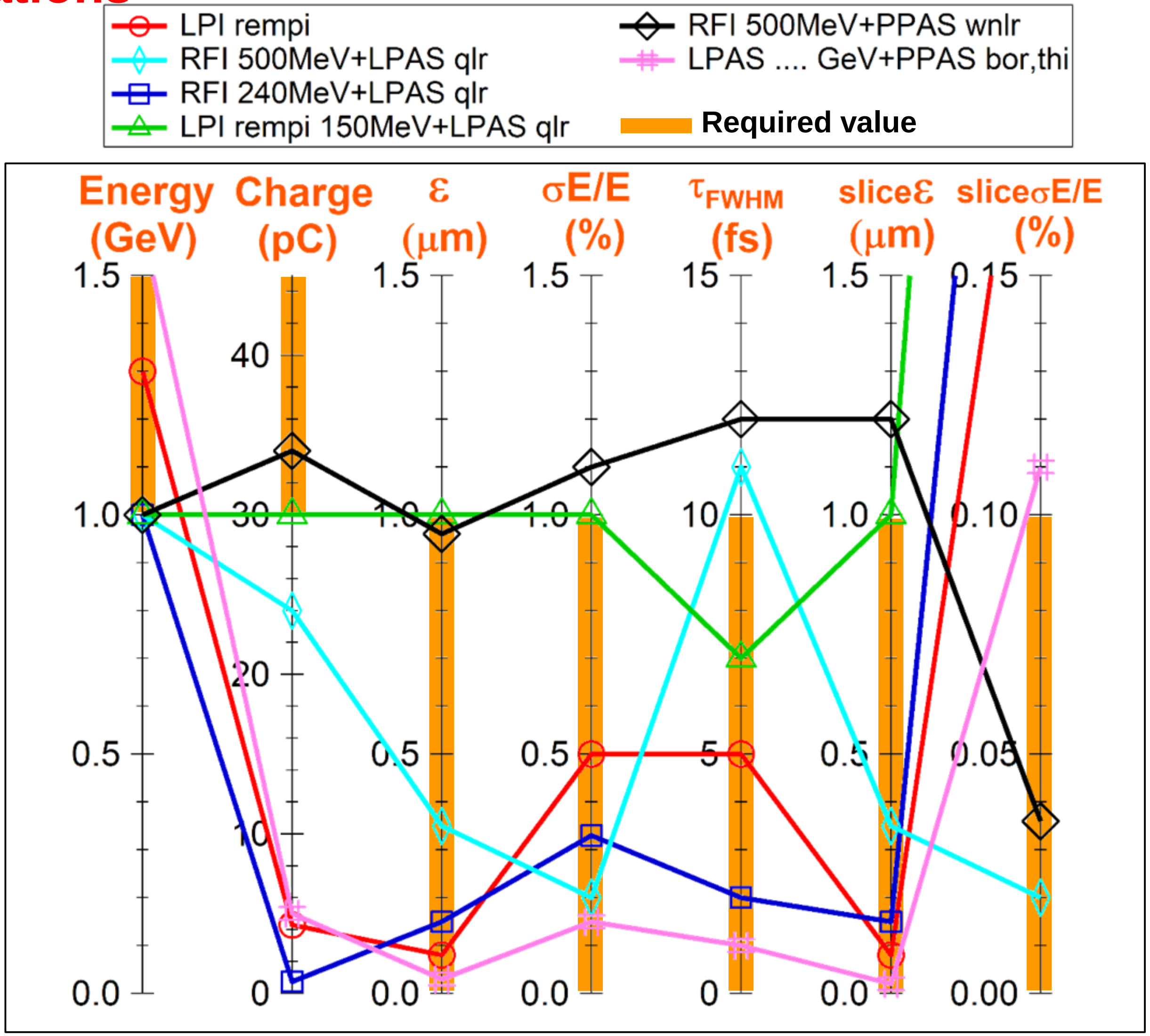
Configurations closest to the requirements

Selected for start-to-end simulation



Beam parameters obtained at 1 GeV

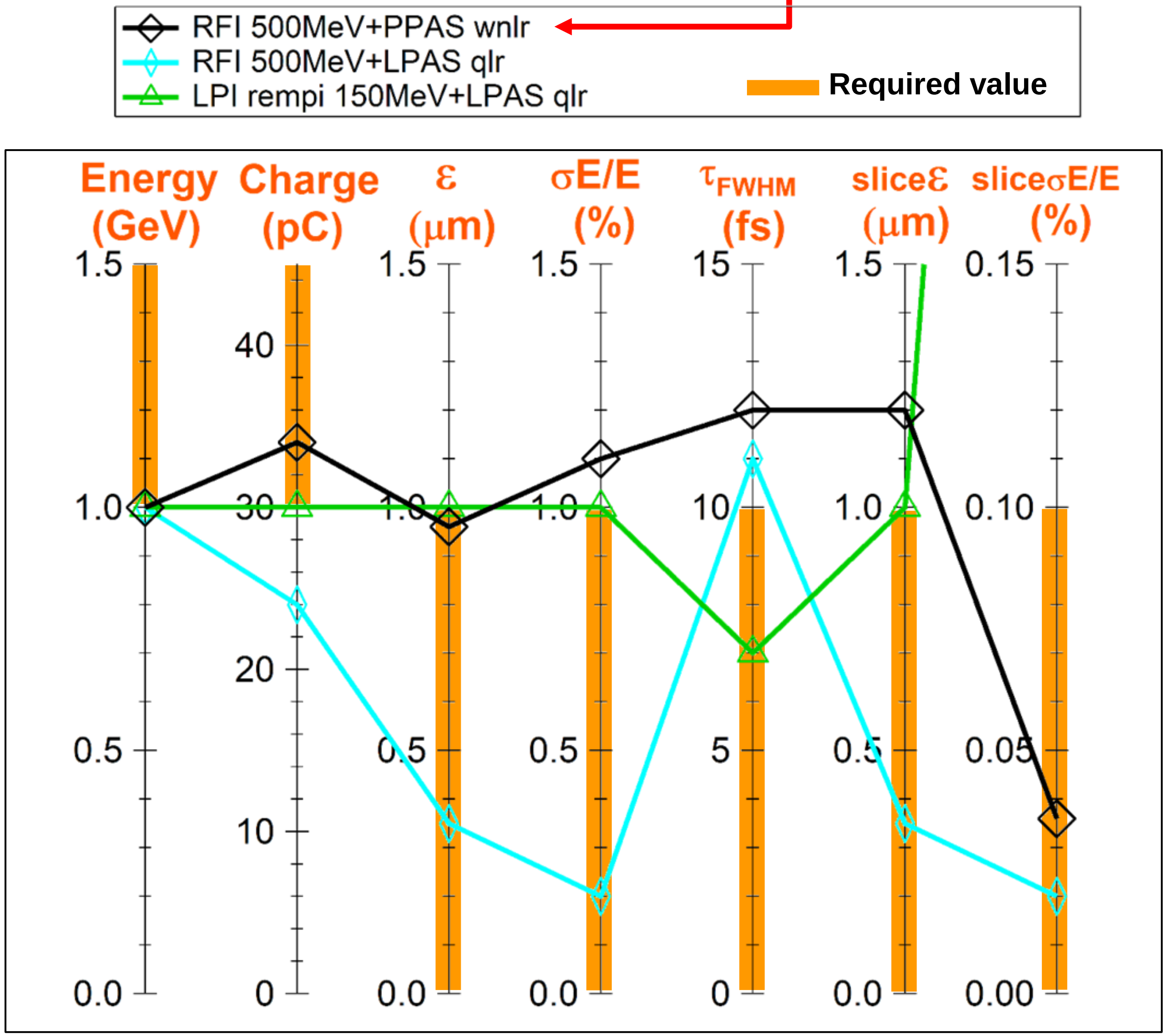
All the configurations



Beam parameters obtained at 1 GeV

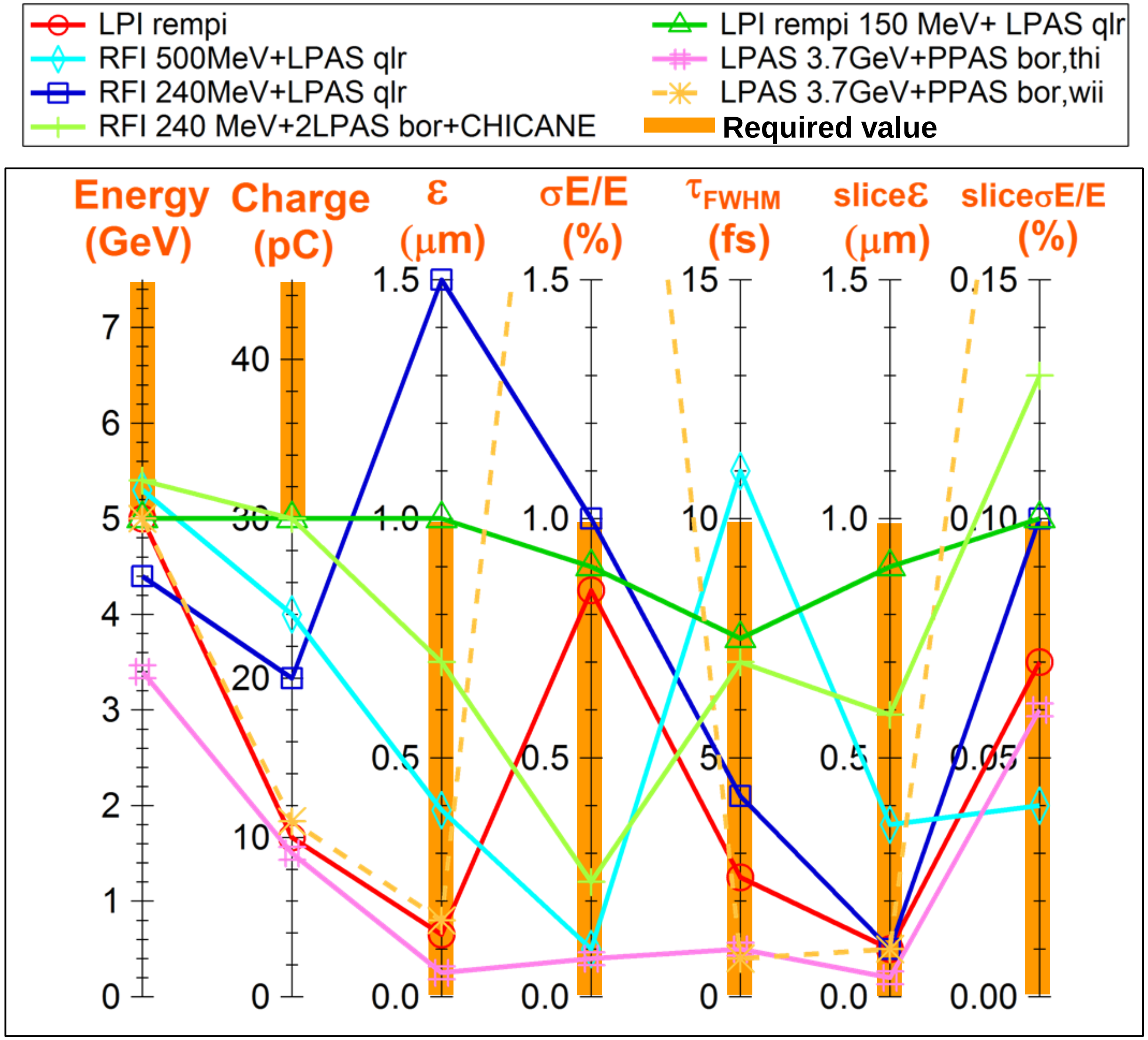
Configurations closest to requirements

Selected for start-to-end simulation



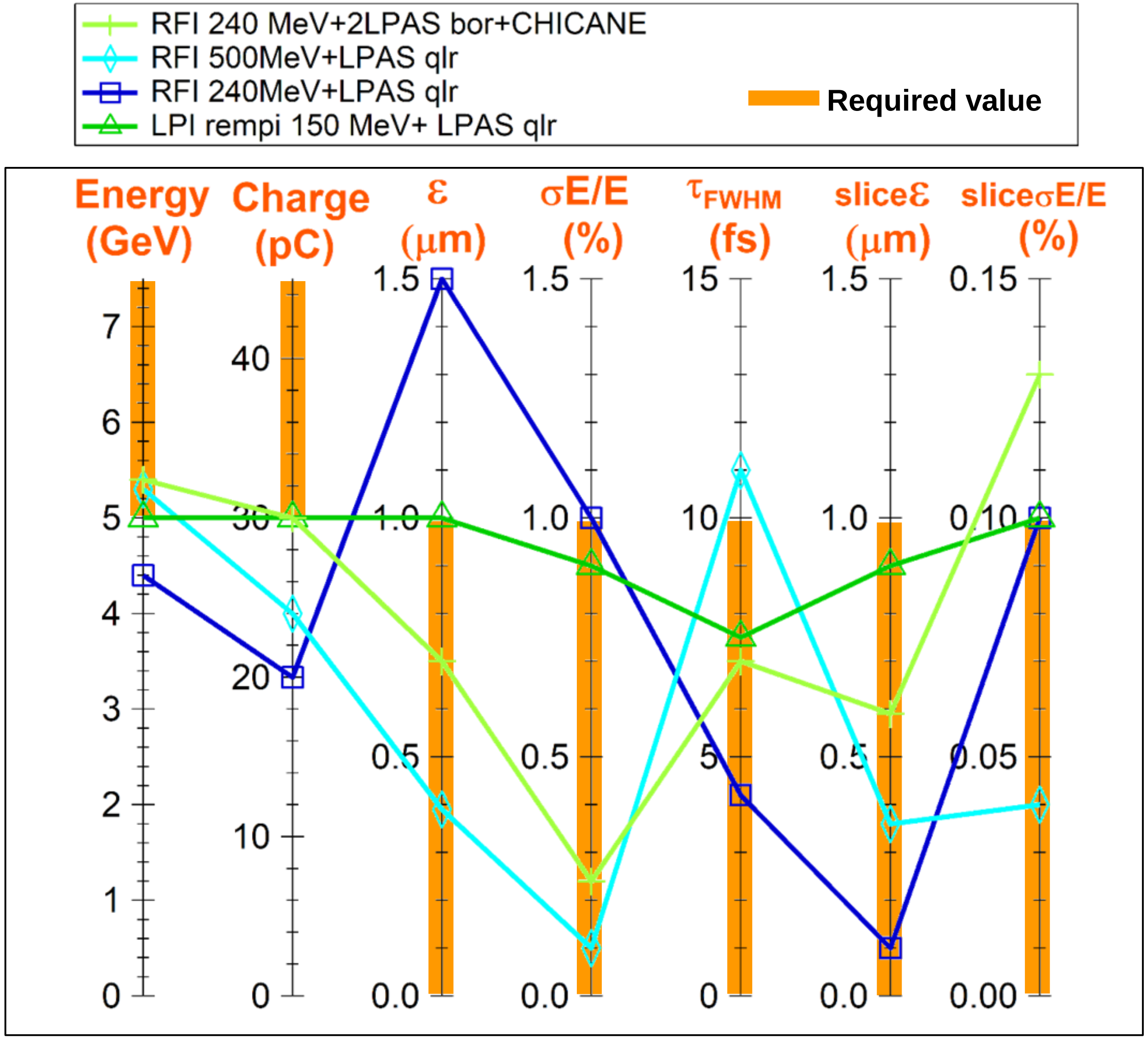
Beam parameters obtained at 5 GeV

All the configurations



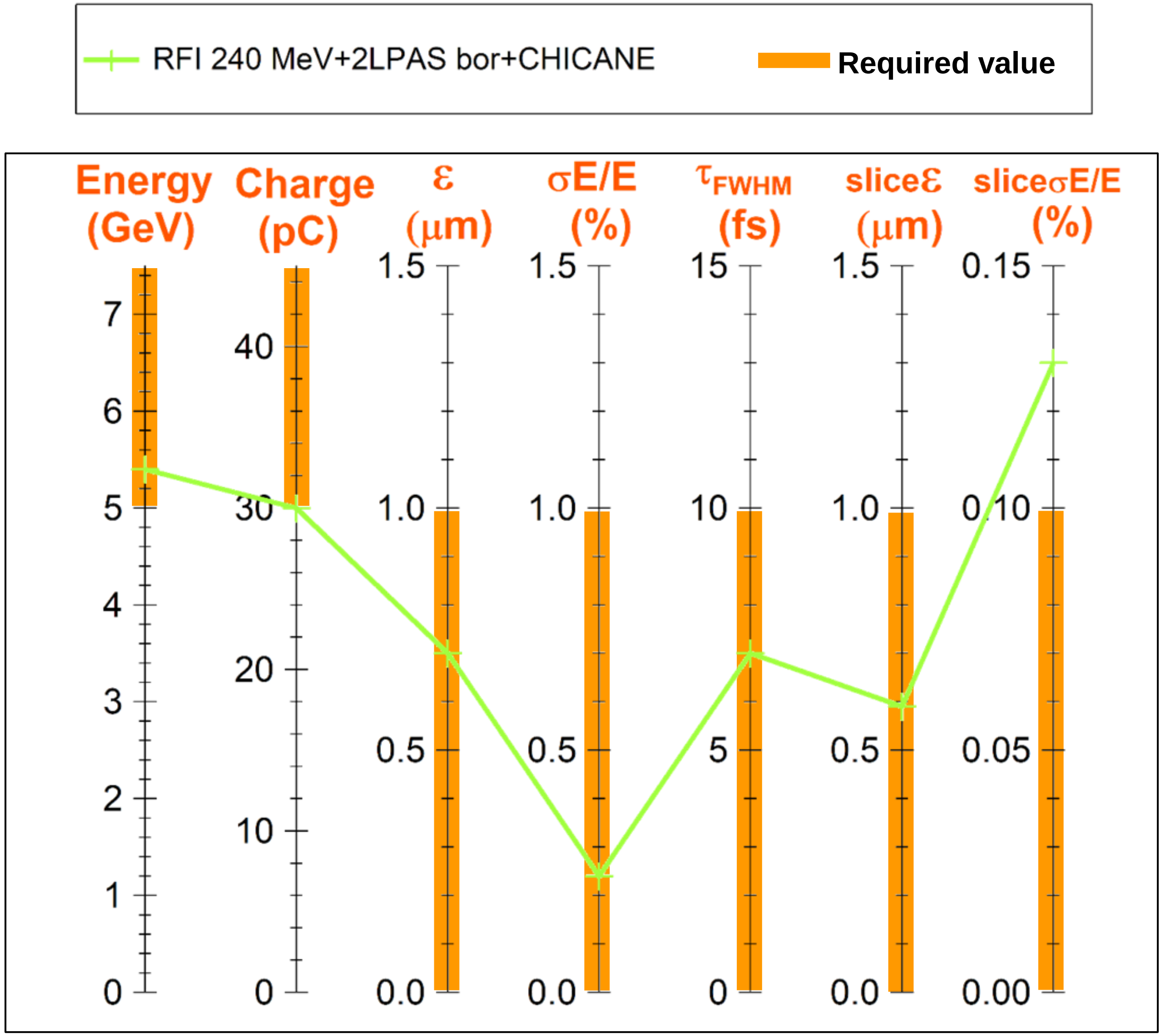
Beam parameters obtained at 5 GeV

Configurations closest to the requirements



Beam parameters obtained at 5 GeV

2-LPAS configuration selected for S2E



Beam parameters obtained at 5 GeV

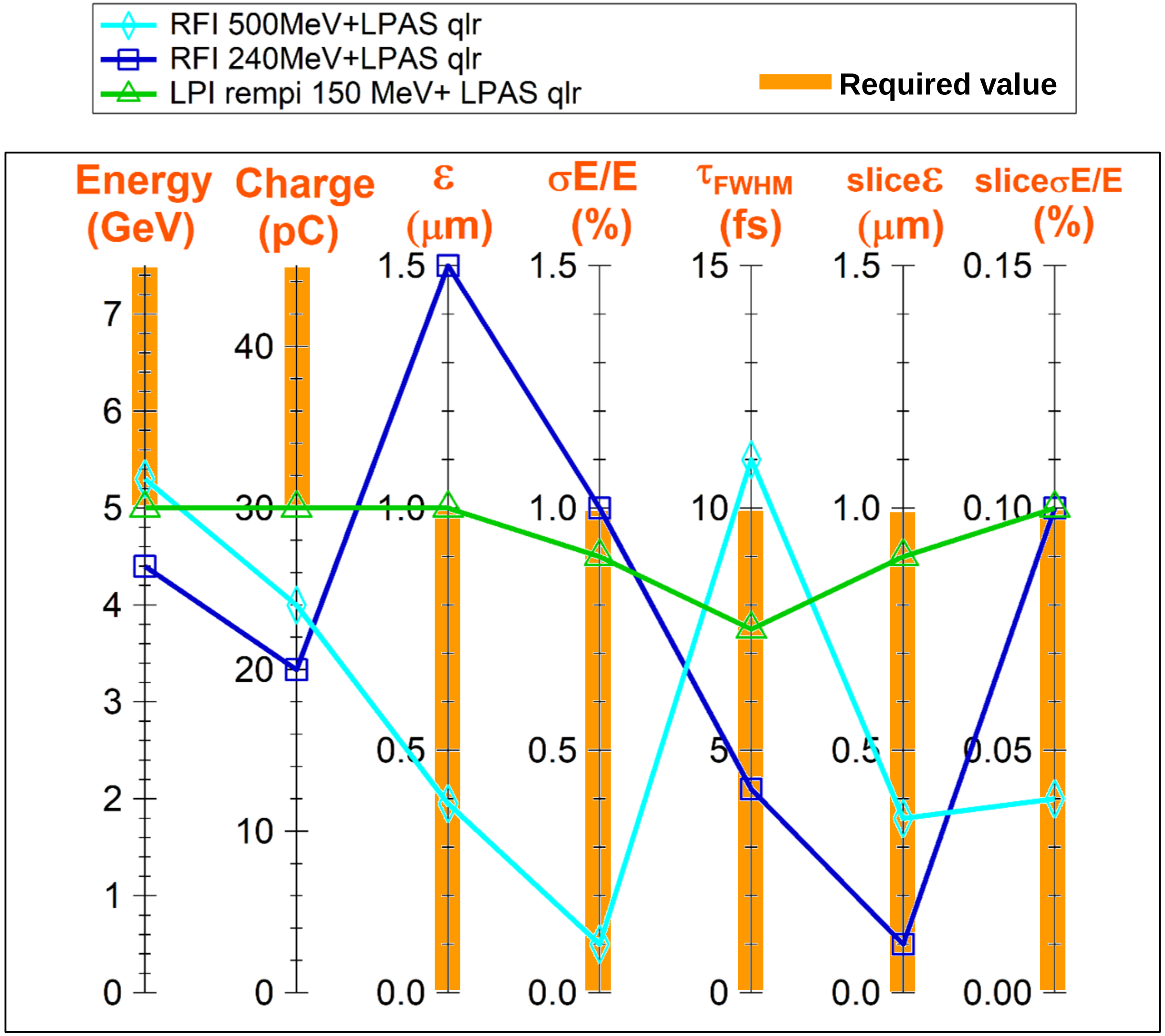
1-LPAS configurations closest to the requirements

Three experts
Three institutes

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

Three injectors:
LPI 150 MeV
RFI 240 MeV
RFI 540 MeV

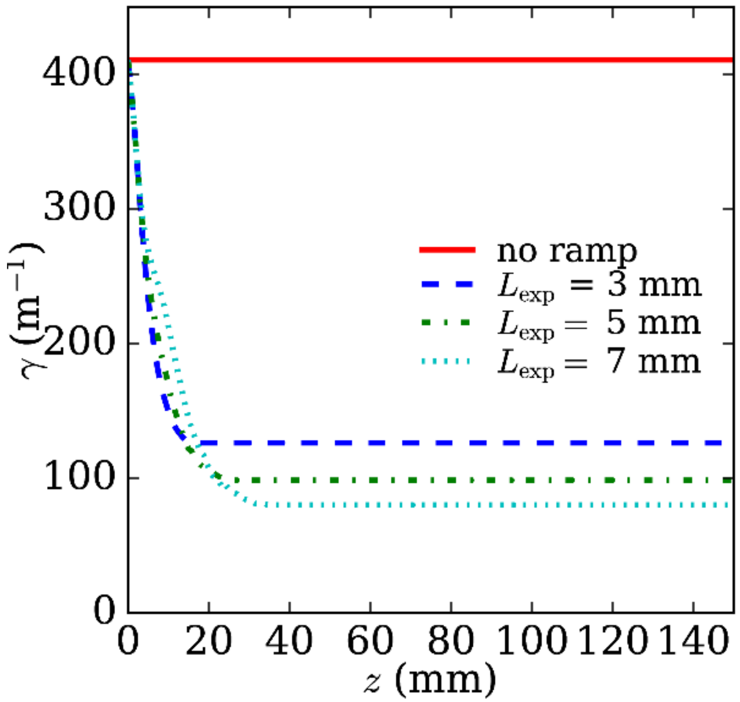
Quasi linear regime
Close plasma,
laser parameters
⇒
Close results

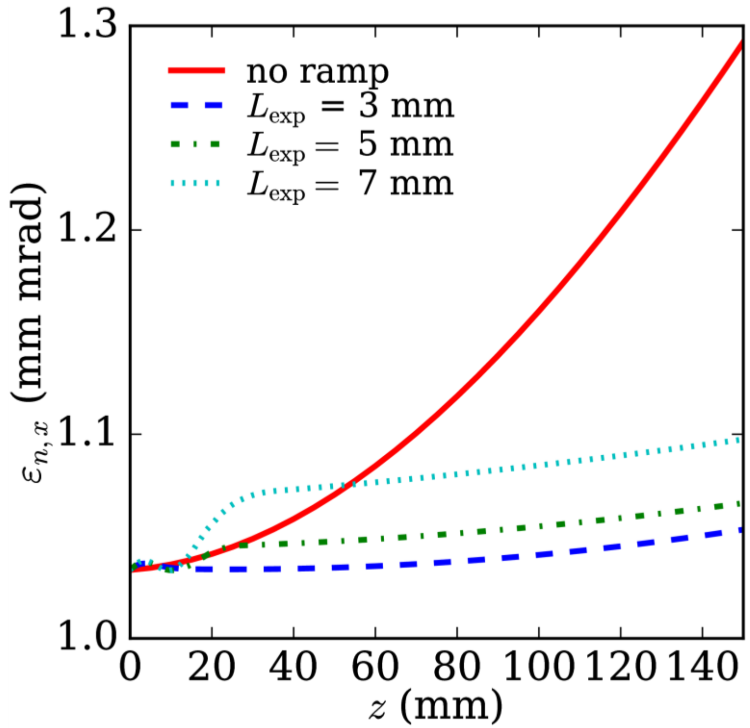


Quasilinear regime with external injection: very robust !!!

To minimize emittance growth, it is imperative to:

1 **Tune the density ramp length, at entrance and exit (whatever its shape!)**





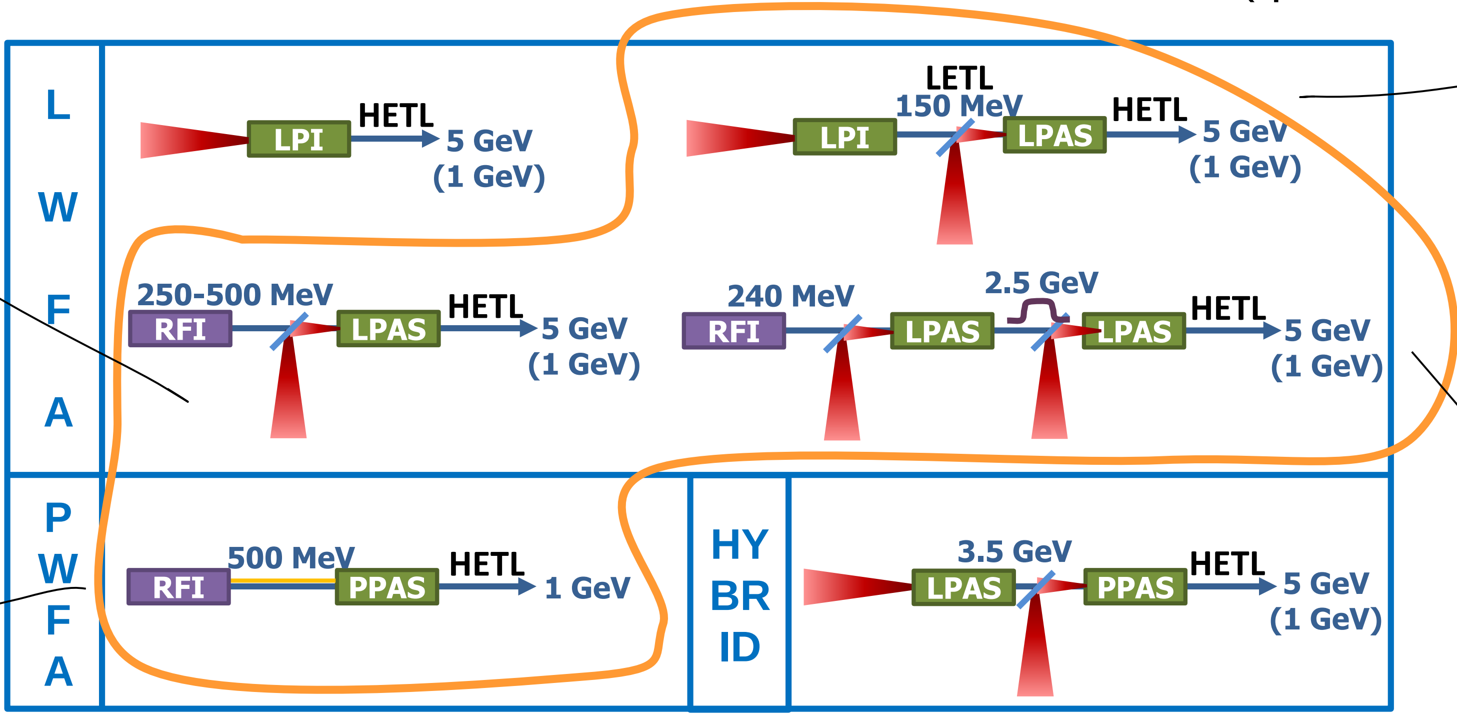
2 **Design transport lines where**
number of quadrupoles = number of constraints (6, no more!)

LETL: 0.7 m, HETL: 4 m ➔ 20% emittance growth throughout a plasma stage

Selected Inj./Acc. Configurations

RFI 250-500MeV +
LPAS (quasilinear regime)

LPI 150 MeV (REMPI) + LPAS
(quasilinear regime)



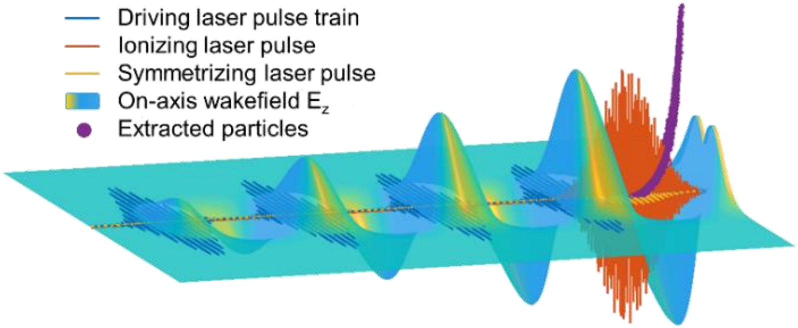
RFI 500 MeV +
PPAS (weakly-nonlinear regime)

RFI 240MeV +
2 LPAS (blow-out regime) +
CHICANE

Decouple injection from acceleration: two stages!
<u>and also</u> in the injection stage itself again!

Notice: a certain level of sophistication is necessary!!

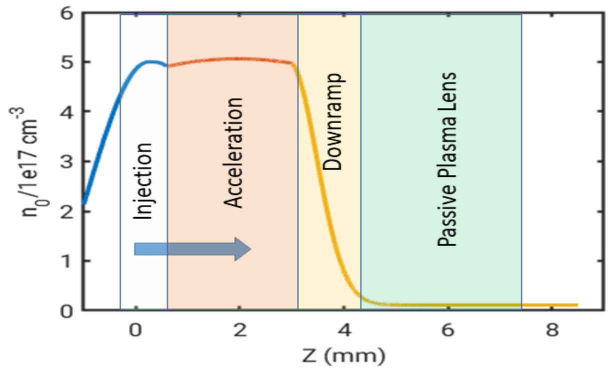
Specifications for laser & plasma at 150 MeV



"ReMPI"

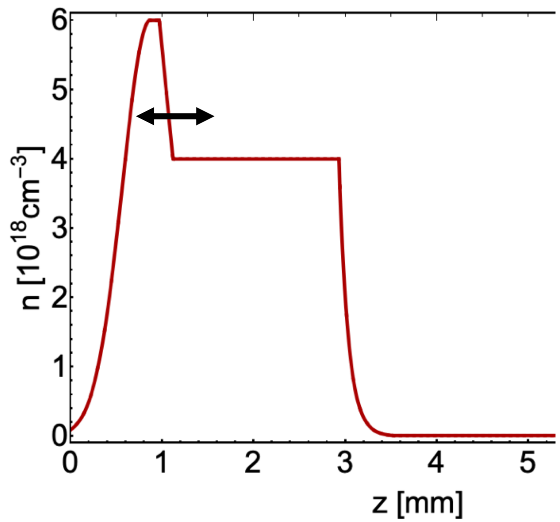
Driving laser: decomposed in 4 subpulses, delay 160 fs
120 TW, 4 J, w_0 = 30 μm (a_0 = 1, τ_{FWHM} = 30 fs)
Ionizing laser: 3rd harmonic
1.0 TW, 0.07 J, w_0 = 3.8 μm (a_0 = 0.53, τ_{FWHM} = 45 fs)
Symmetrization laser: 3rd harmonic, delay 40 fs
0.7 TW, 0.02 J, w_0 = 11 μm (a_0 = 0.14, τ_{FWHM} = 25 fs)

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}



OR ELSE
"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}



Spécifications for laser & plasma at 1 & 5 GeV

1 GeV

Laser: P = 200 TW, E = 30 J, w_0 = 30 μm (a_0 = 2.57, τ_{FWHM} = 141 fs)
Bi gaussian

Plasma: parabolic in r, $\Delta n/n_c$ = 1 to 0.6
unniform in z, 5 to 7 cm long, n_0 = 1 to 2 10^{17} cm^{-3}
entrance and exit ramps ~2 cm

5 GeV

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

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

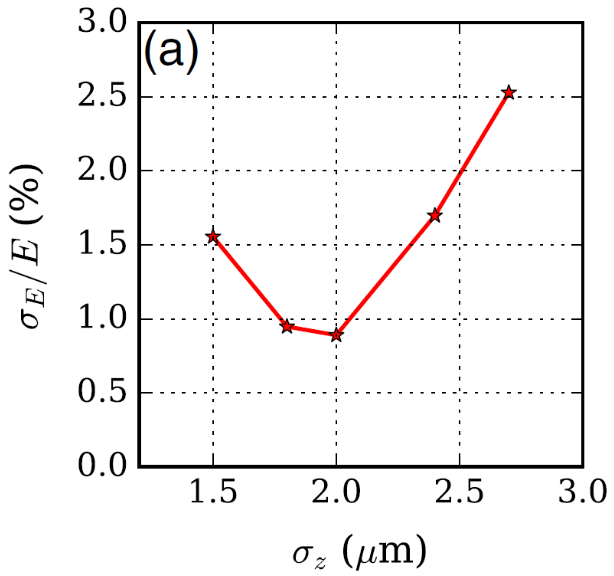
Solutions do exist, at least one is robust

Other schemes or techniques remain promising
Further progress is still possible

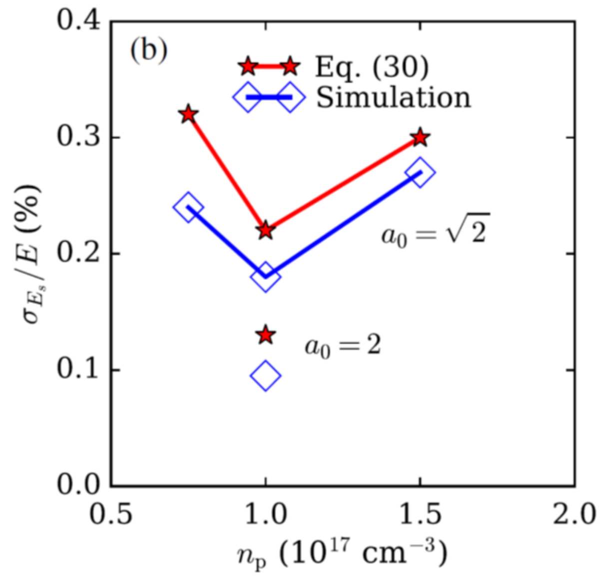
Next step: Errors and Tolerances studies

RESERVE

In the presence of significant beam loading



Optimizing energy spread
by optimizing the beam length



Optimizing slice energy spread
by optimizing jointly
the plasma density
and the laser rtength