Le projet d'accélérateur plasma EuPRAXIA

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on behalf of the EuPRAXIA collaboration

25e Congrès Général de la Société Française de Physique

EuPRAXIA:

Un projet Européen

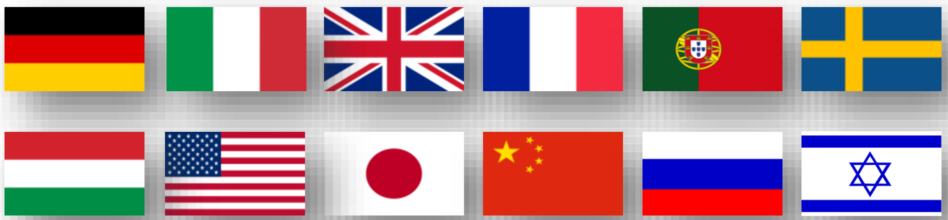
visant à produire un CDR

pour la construction du premier accélérateur au monde

basé sur les techniques d'acceleration par champ de sillage

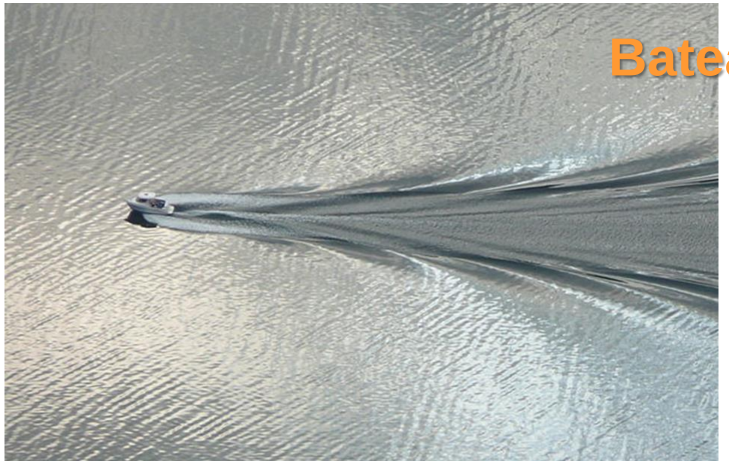
capable de délivrer un faisceau d' e^- de 5 GeV de qualité industrielle

à des communautés d'utilisateurs (LEL, PHE, autres)



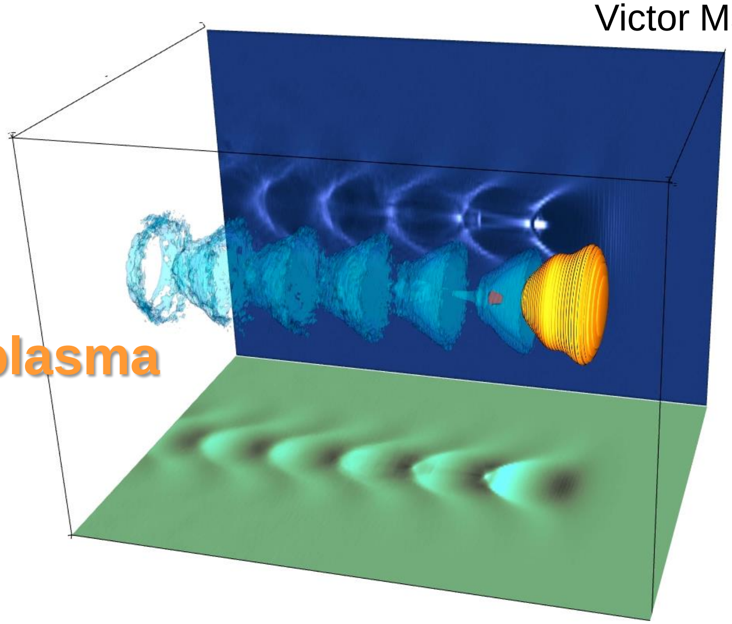
Sillage

Bateau dans l'eau



Avion dans l'air

Victor Malka



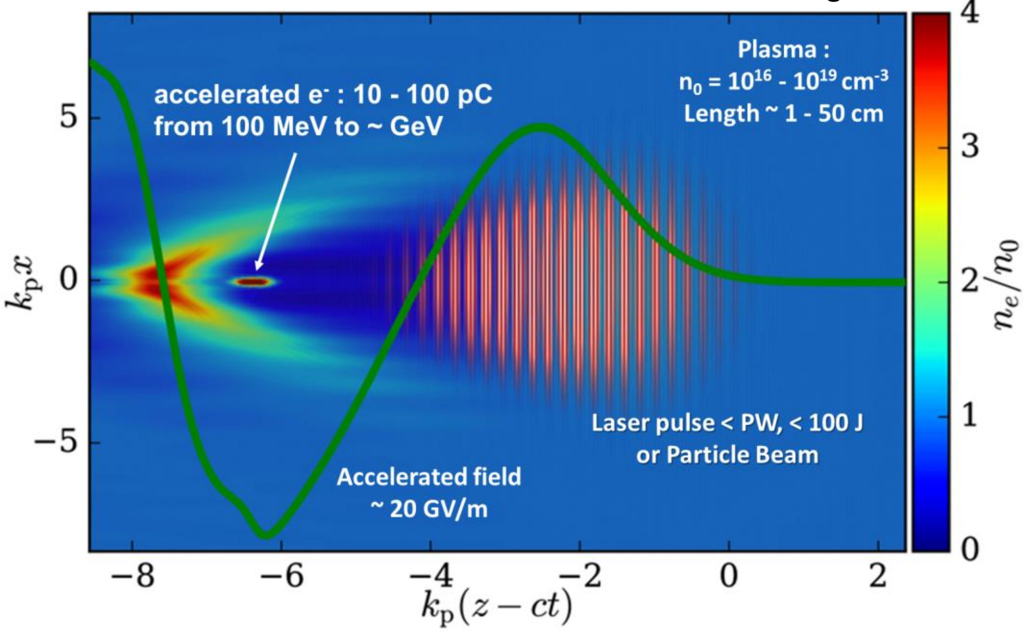
Laser dans un plasma

Champ de sillage dans un plasma

Suggestions de
Veksler, 1956
Tajima & Dawson, PRL 1979

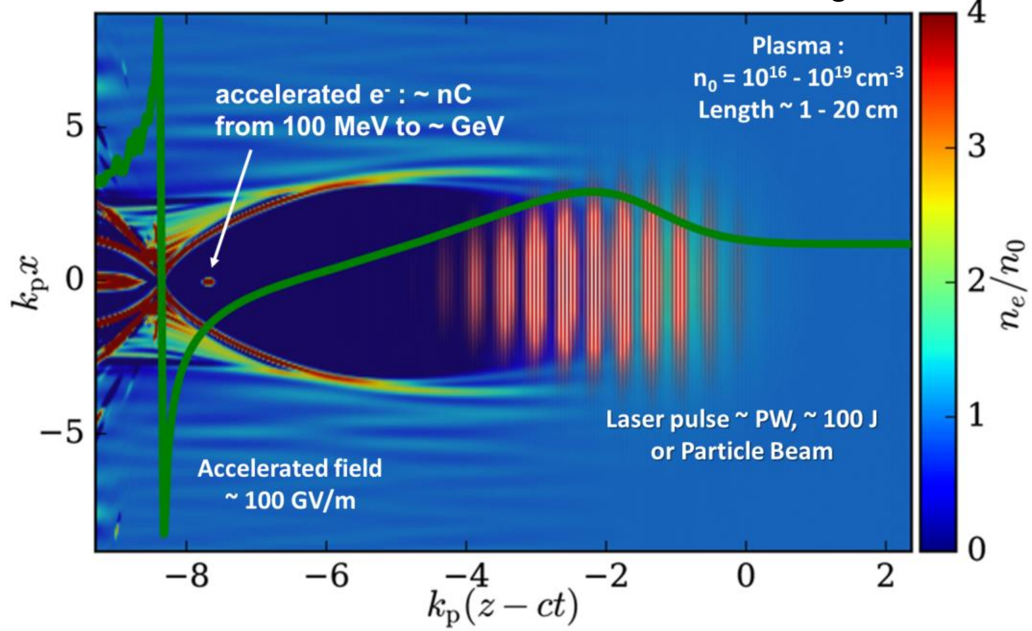
Laser pulse or Particle beam in a Plasma
→ Wake: Cavity, e^- pushed toward the border
→ Coulomb force, mm → Huge wake field
→ Accelerating cavity and … focusing element

Xiangkun Li



Quasi-Linear acceleration regime

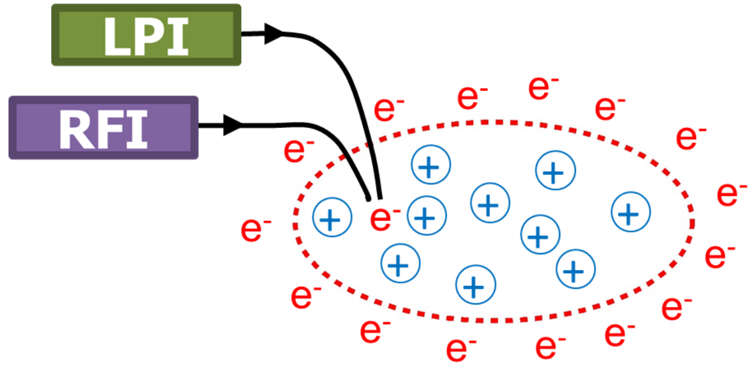
Xiangkun Li



Nonlinear acceleration regime

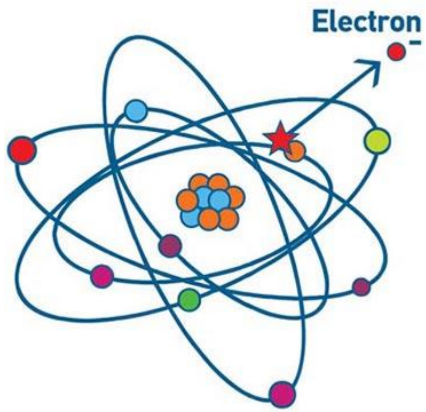
Injection

External injection,
from a conventional RF accelerator or another plasma wake-field accelerator



Self injection,
by the wave-breaking mechanism, when background electron speed is higher than wake field speed

Injection by laser ionization



Concept d'acceleration par champ de sillage

Accelerating field + Focusing gradient + Injection mechanism = ACCELERATOR

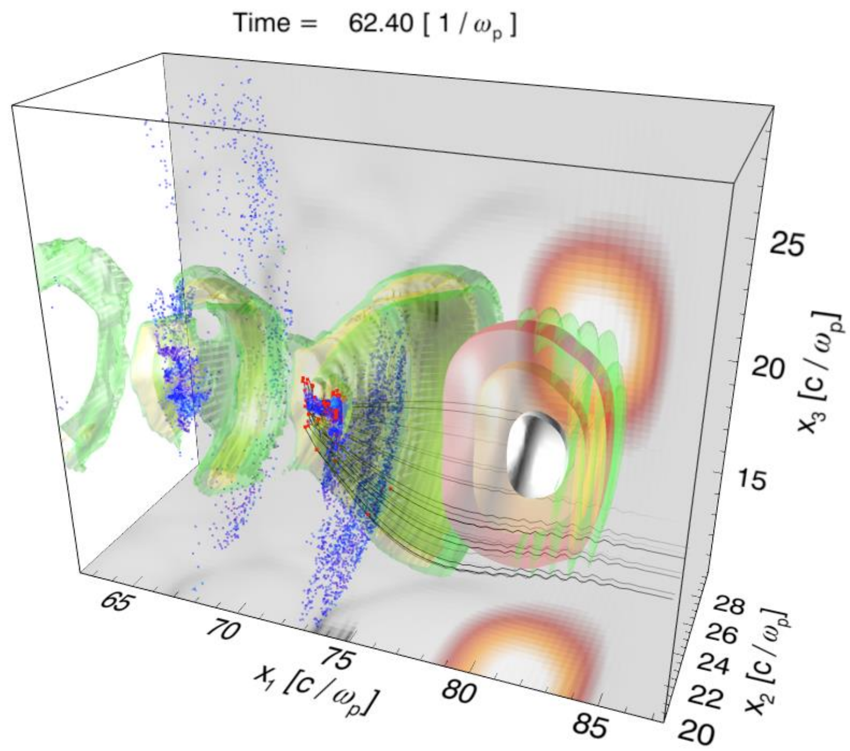
~ GV / m **~ 10^5 m^{-2}** **3 orders of magnitude > RF accelerator**

Limitations

- Laser diffraction
- Laser depletion
- Dephasage
- Beam loading

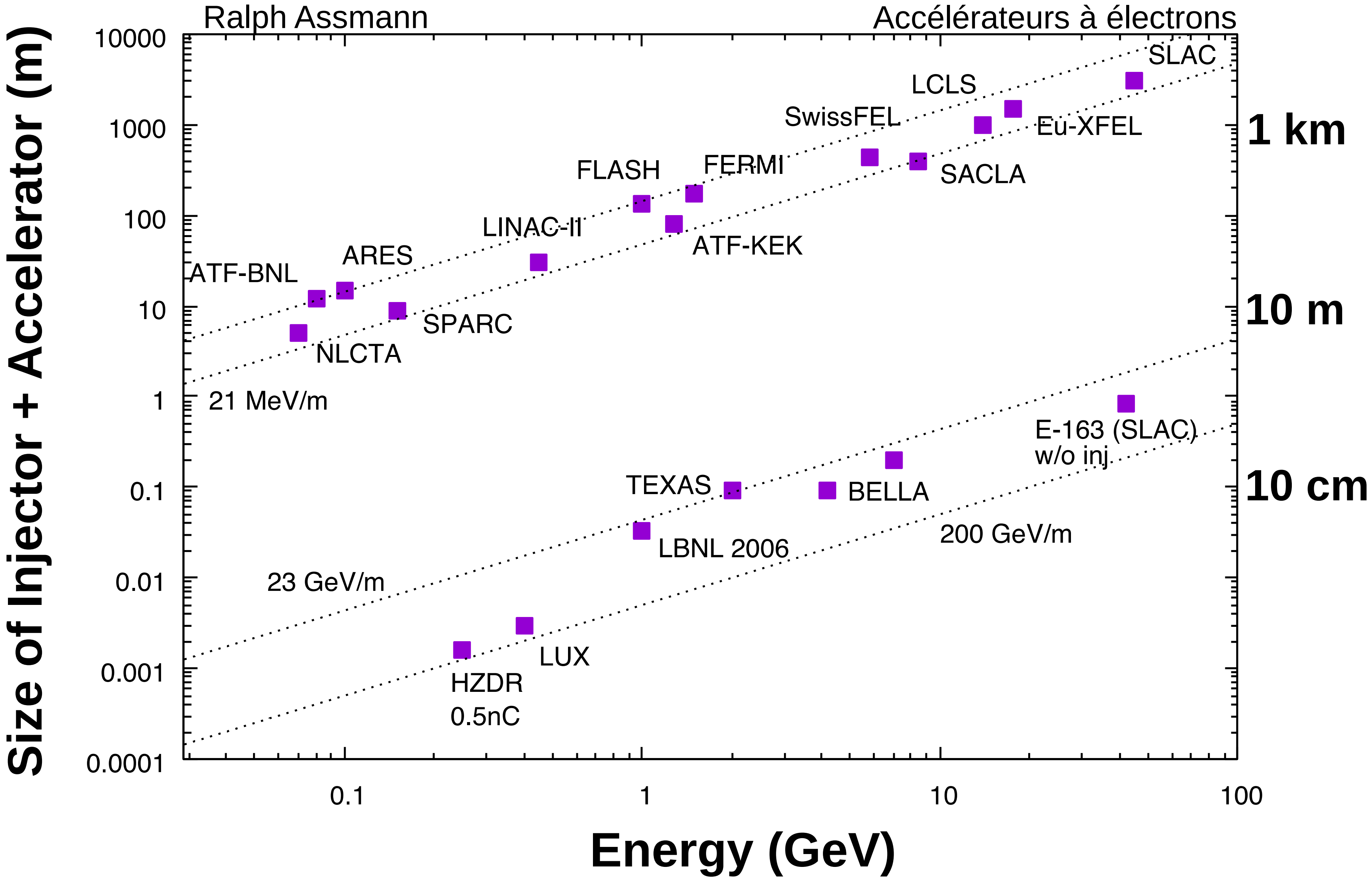
- Beam quality

- Small repetition rate 10 **Hz**
- Bulky laser system (PW)

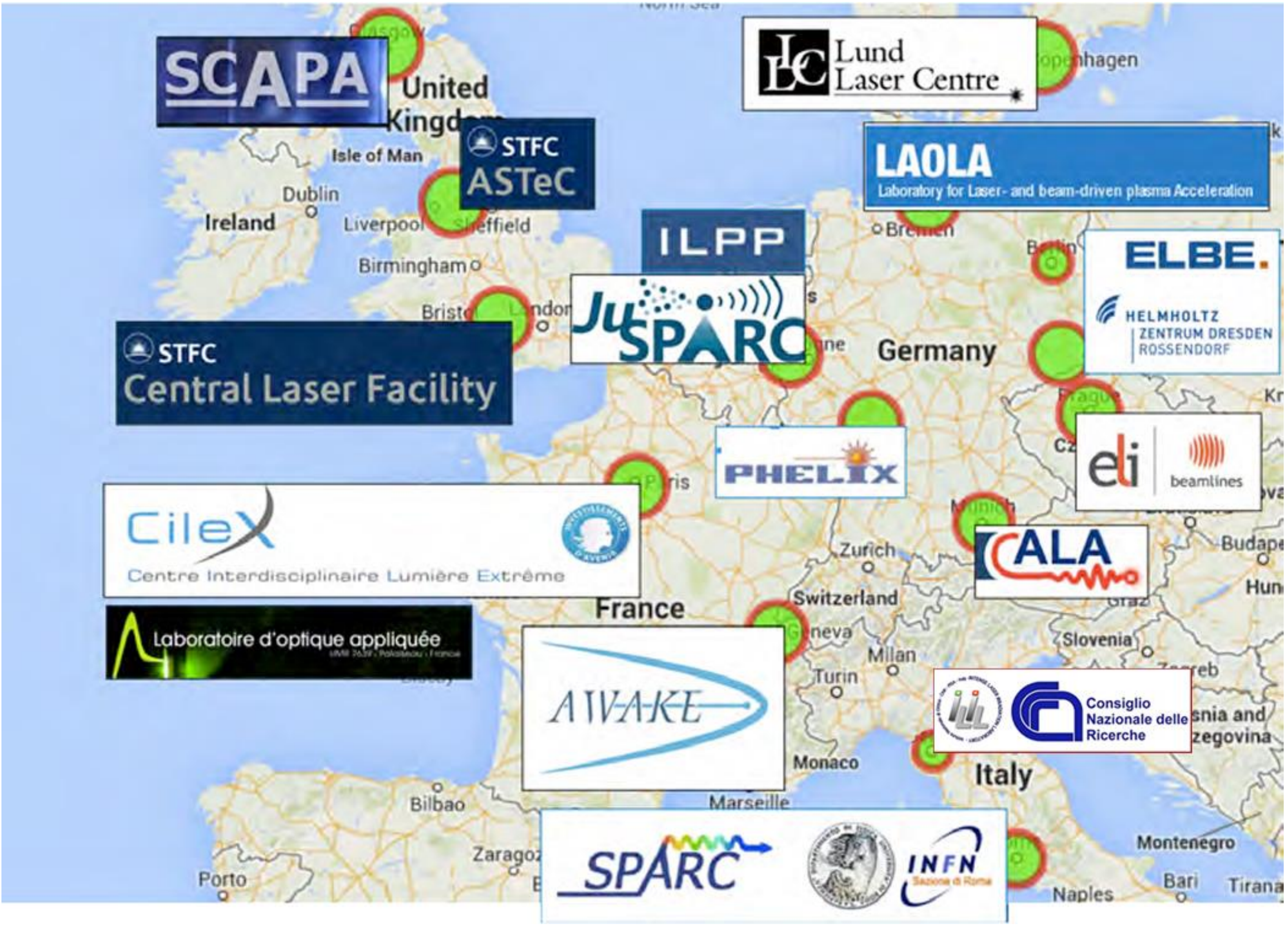


Luis O. Silva

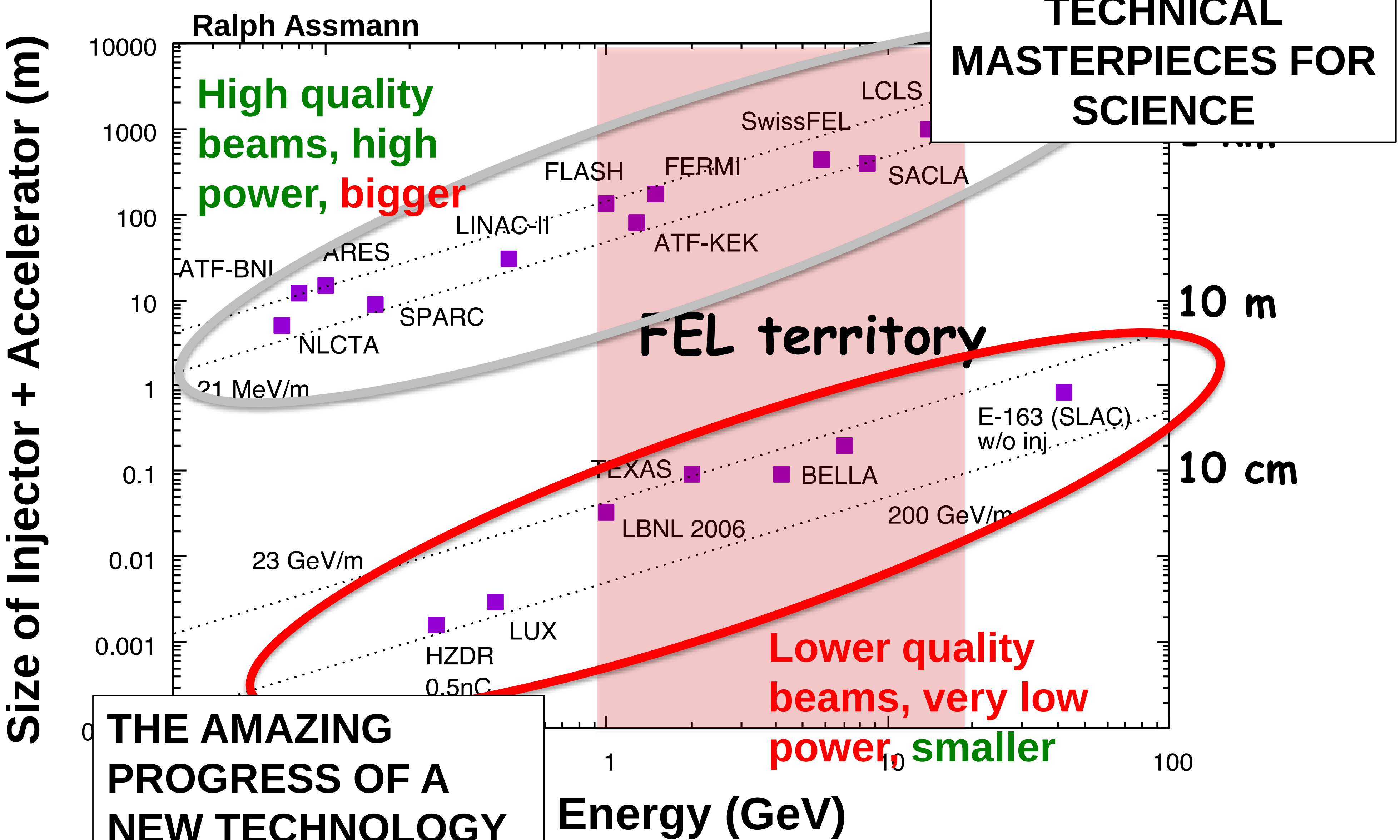
Taille vs Energie



Plus particulièrement en Europe



Taille et Qualité faisceau

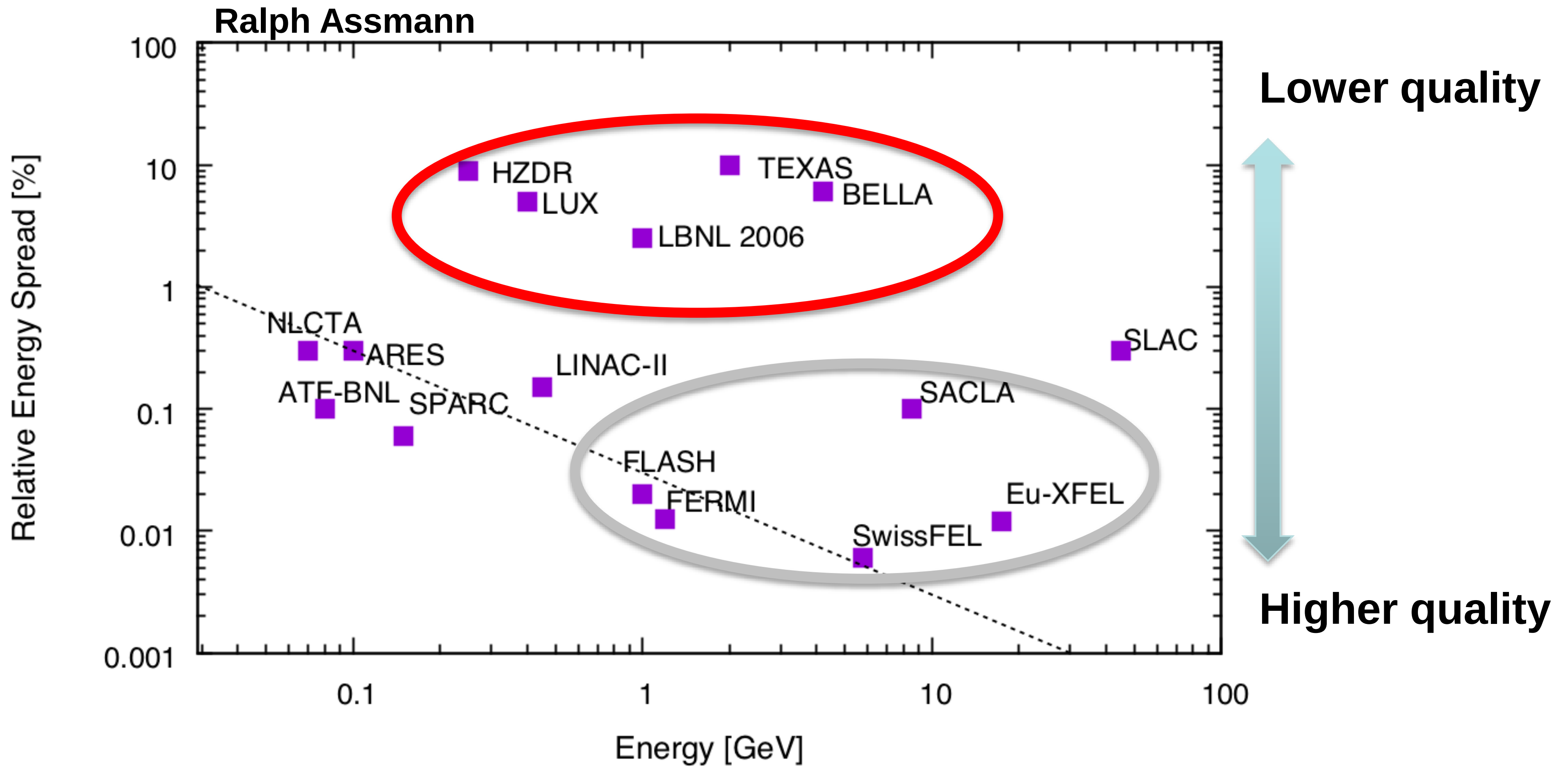


TECHNICAL MASTERPIECES FOR SCIENCE

THE AMAZING PROGRESS OF A NEW TECHNOLOGY

Qualité faisceau

Example: energy spread



Franchir une étape de plus

Maturité de l'accélération plasma

Démonstration de son utilisation

Contributions décisives de l'Europe
Industriels laser de renom en Europe
Grands centres d'accélérateurs en Europe

DE la preuve de principe À une installation avec utilisateurs

EuPRAXIA Consortium

16 Participants

25 Partenaires Associés

Industriels

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**

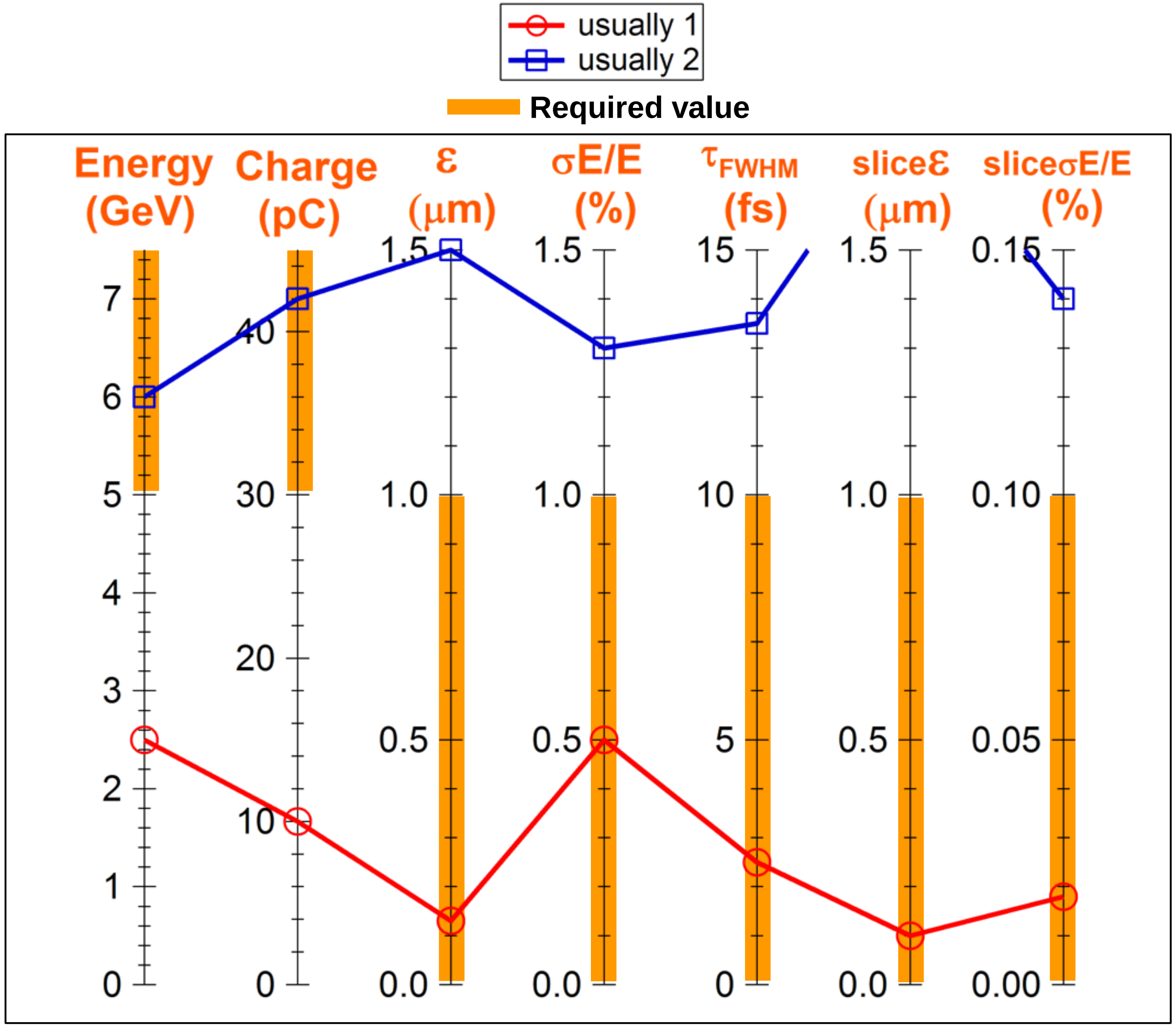
Simultaneously !

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

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

chez l'utilisateur même!

Beam parameters at 5 GeV at the user's doorstep



Démarche "Accélérateur"

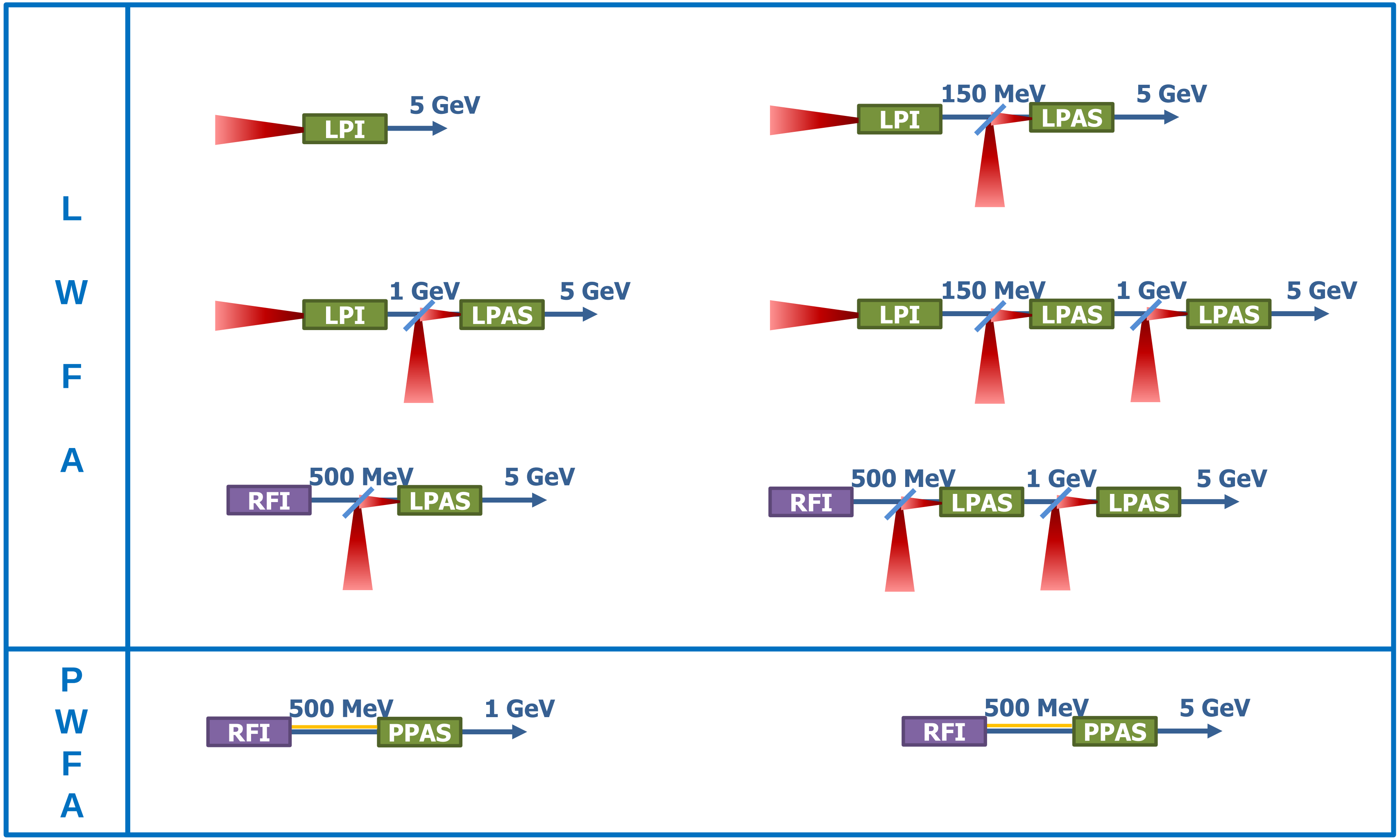
Démarche "Expérience de Physique" : construction autour d'une installation laser

Démarche "Accélérateur" : comme pour un accélérateur conventionnel

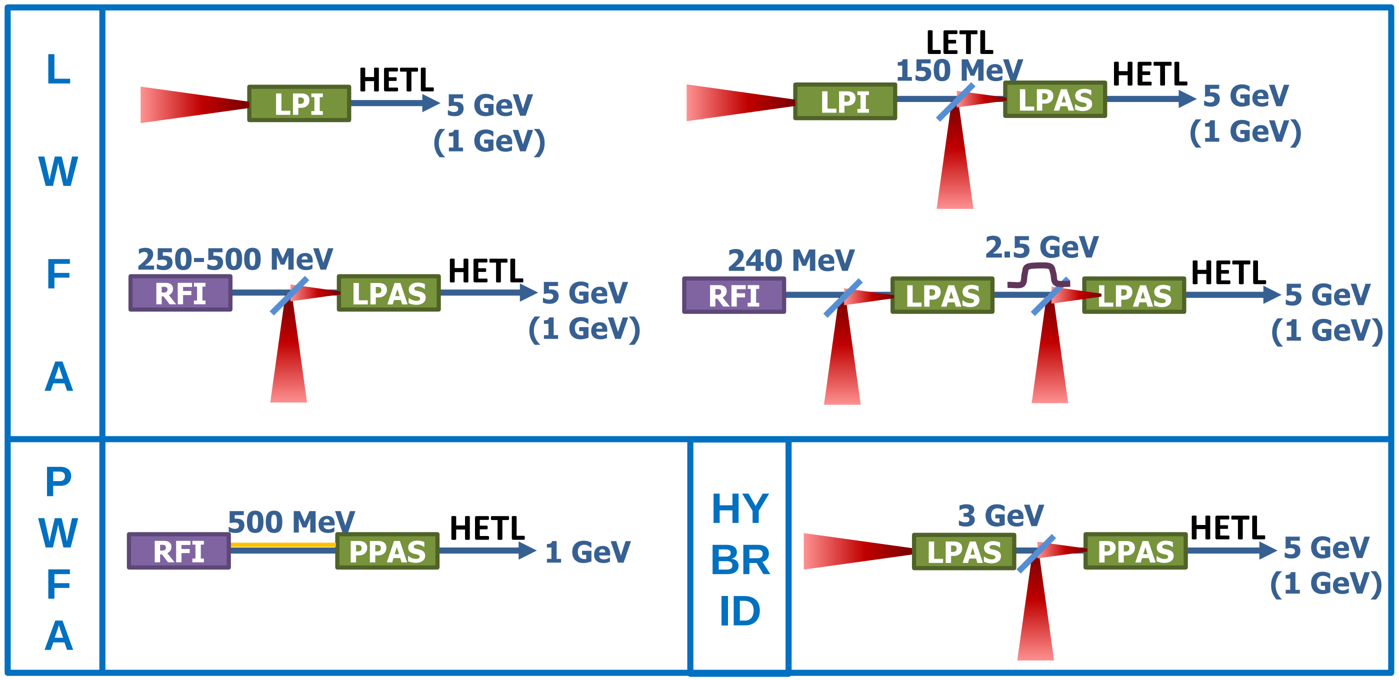
1. Fixation des objectifs faisceau à atteindre (TLR)
2. Large exploration (par simulation) de configurations d'accélération
3. Sélection de la, des configurations répondant aux critères
4. Détermination des spécifications pour les systèmes laser et plasma

Problèmes : en Acc. Laser Plasma
- Les simulations sont très longues
- Beaucoup de codes de simulation
- Fiabilité, robustesse des codes reste à démontrer

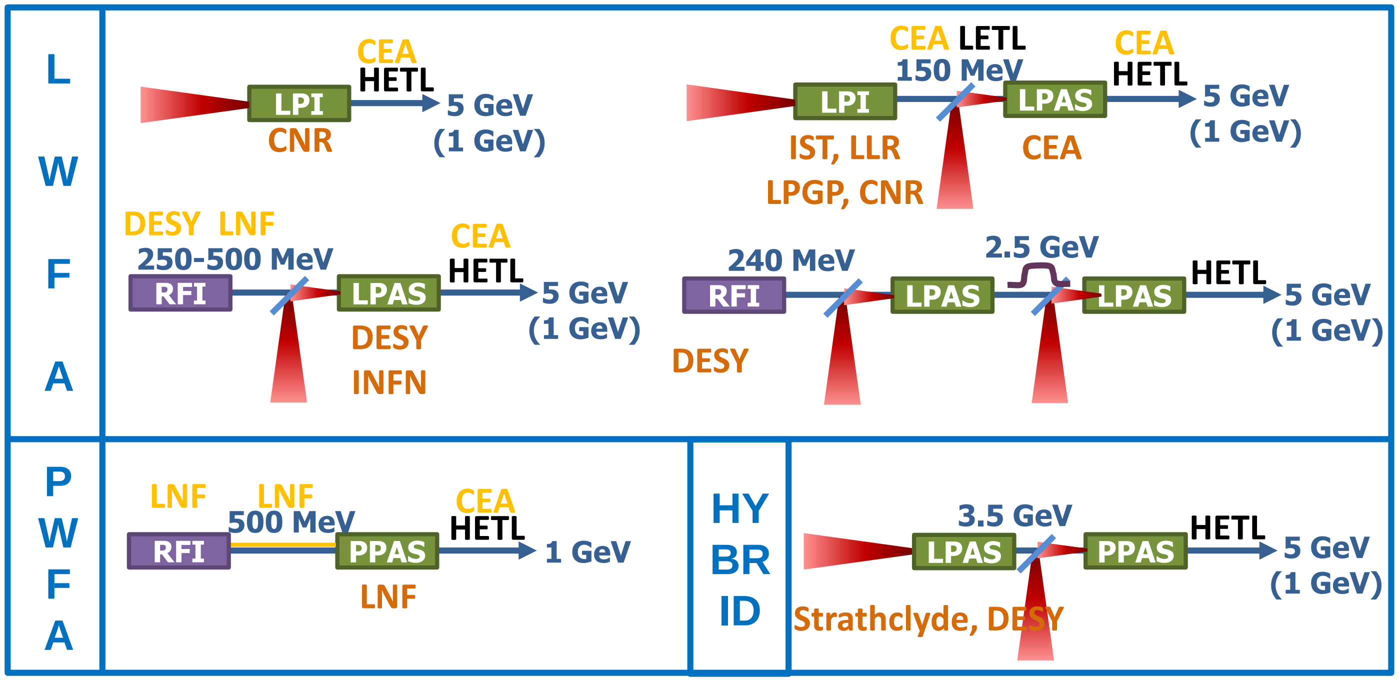
Schémas Inj./Acc. envisagés



Schémas Inj./Acc. étudiés



Techniques Inj./Acc. étudiées



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Techniques Inj./Acc. étudiées

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	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

Techniques Inj./Acc. étudiées

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 Induced Ionization Injection and blow-out regime	OSIRIS

Résultats publiés

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).

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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).

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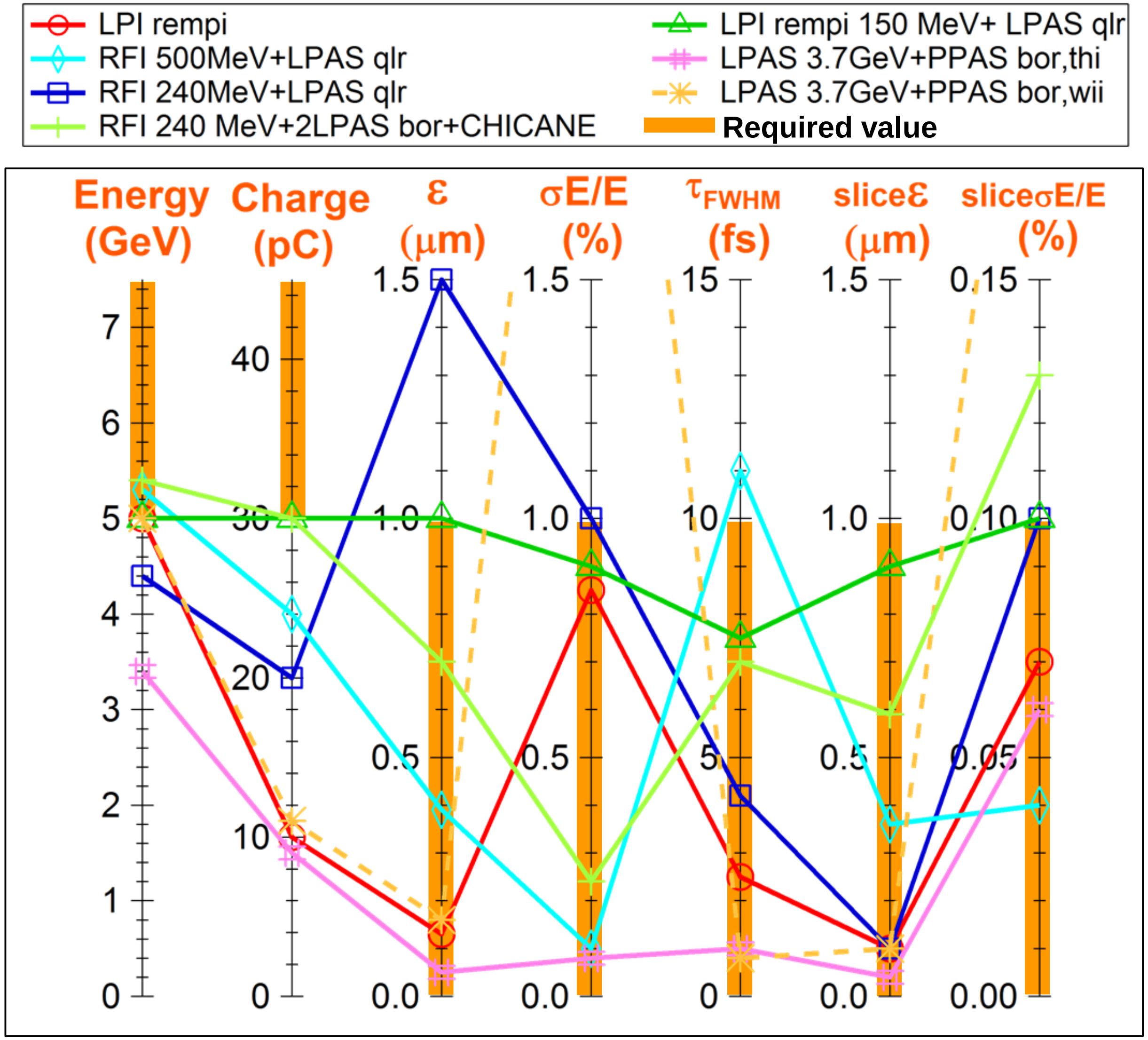
Correlated Energy Spread Compensation in Multi-Stage Plasma-Based Accelerators, A. Ferran Pousa, A. Martinez de la Ossa, R. Brinkmann, and R. W. Assmann, arXiv:1811.07757 [physics.acc-ph], (2018).

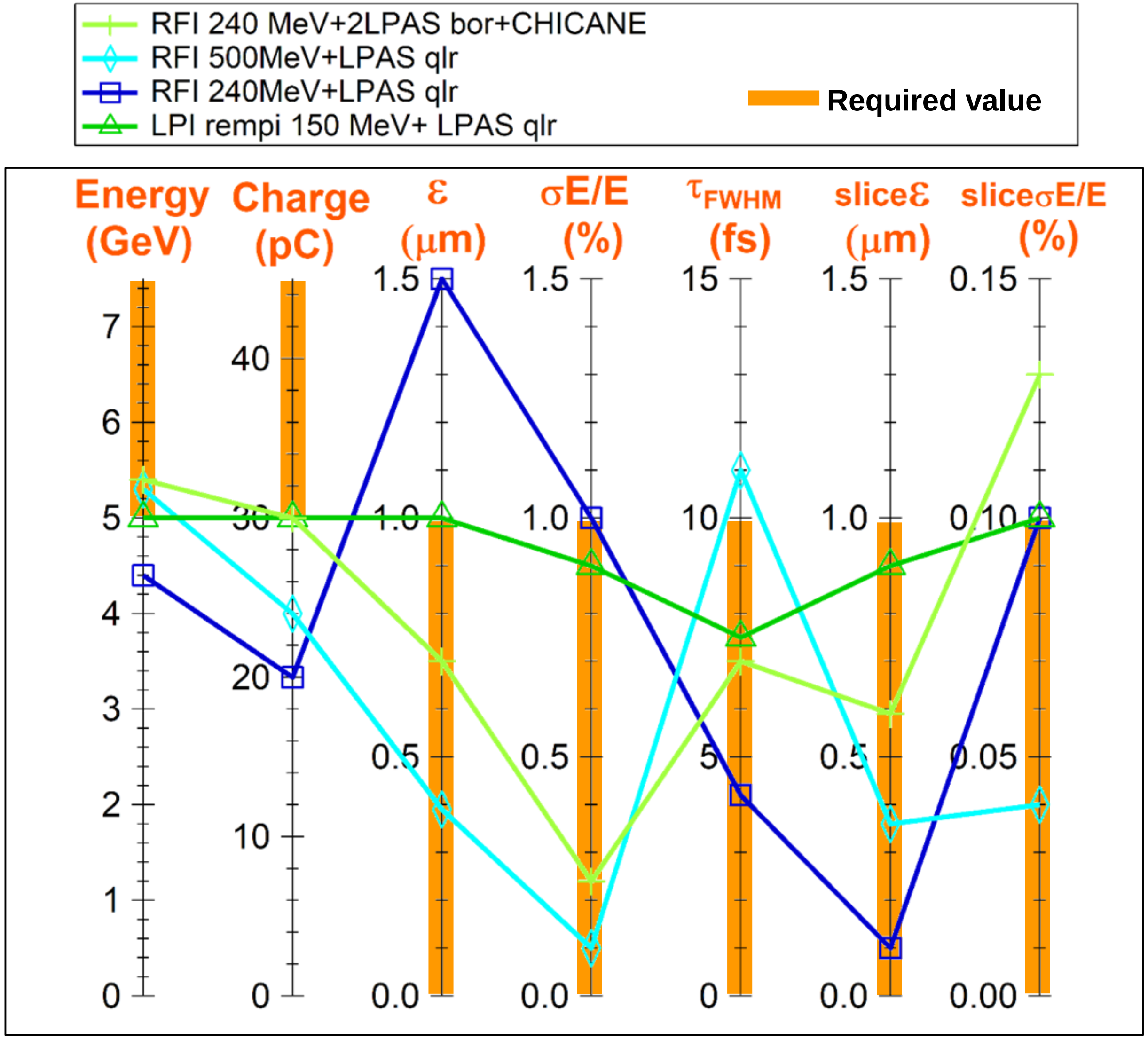
Preserving emittance by matching out and matching in plasma wakefield acceleration stage, X. Li, A. Chancé, P. A. P. Nghiem, Phys. Rev. Accel. Beams, 22, 021304 (2019).

And others ………….

All the configurations



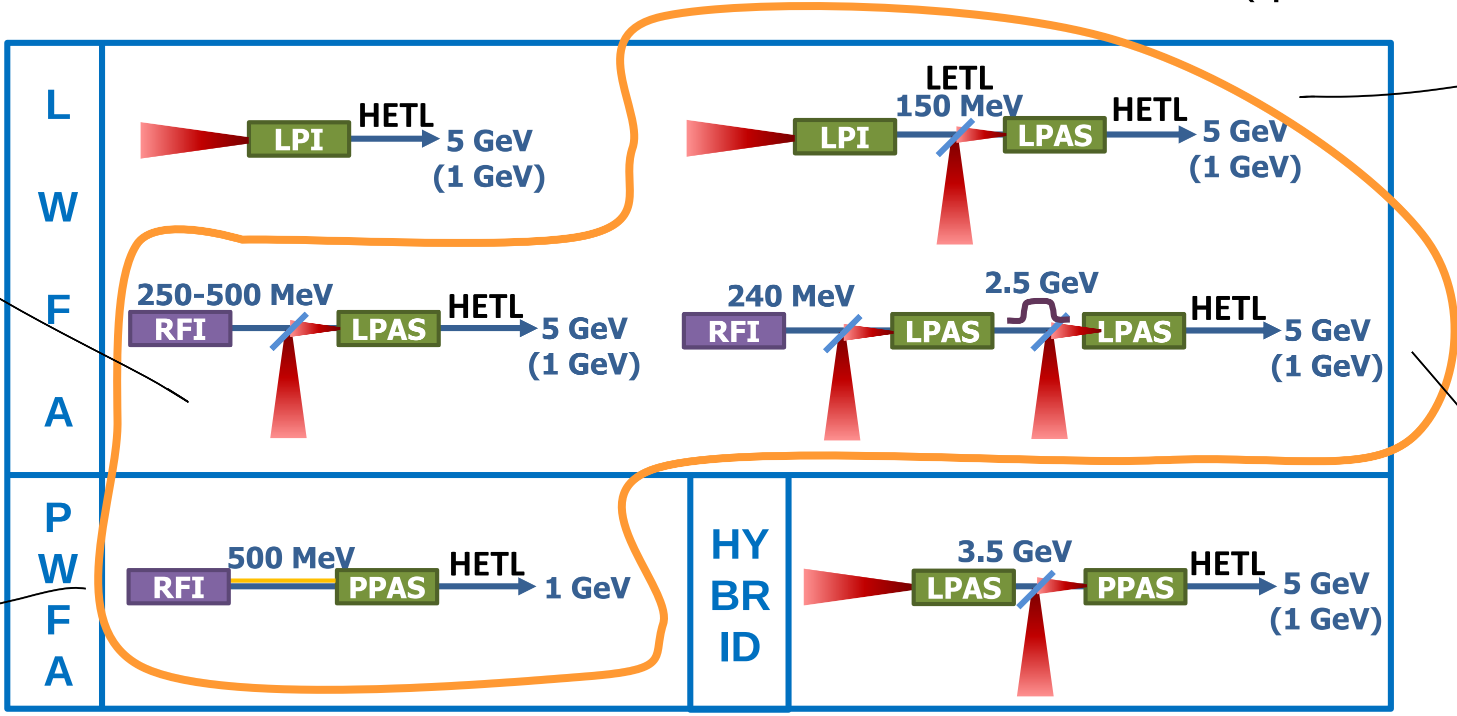
Configurations closest to the requirements



Configurations Inj./Acc. sélectionnées

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

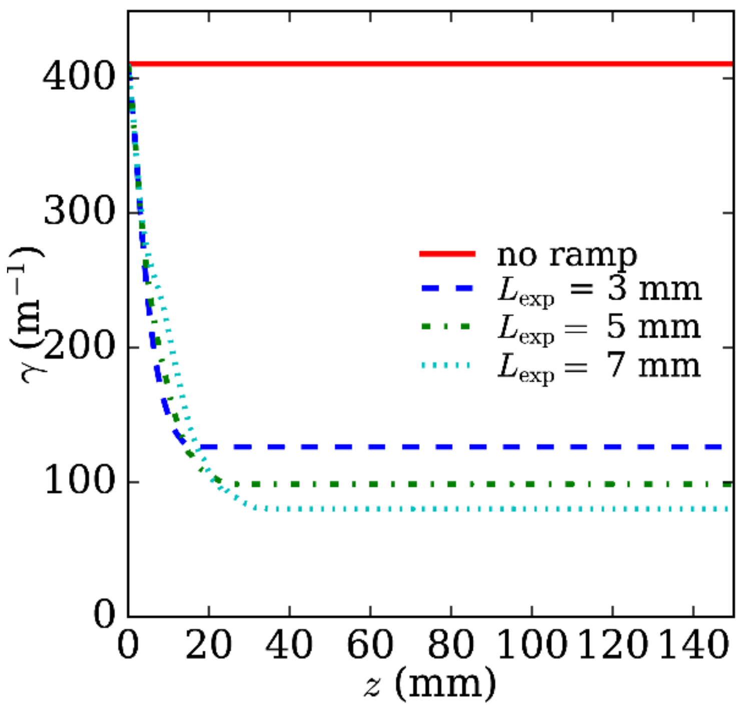
Découpler Injection / Acceleration: deux étages !
<u>et de même</u> pour le stage d'injection lui-même !

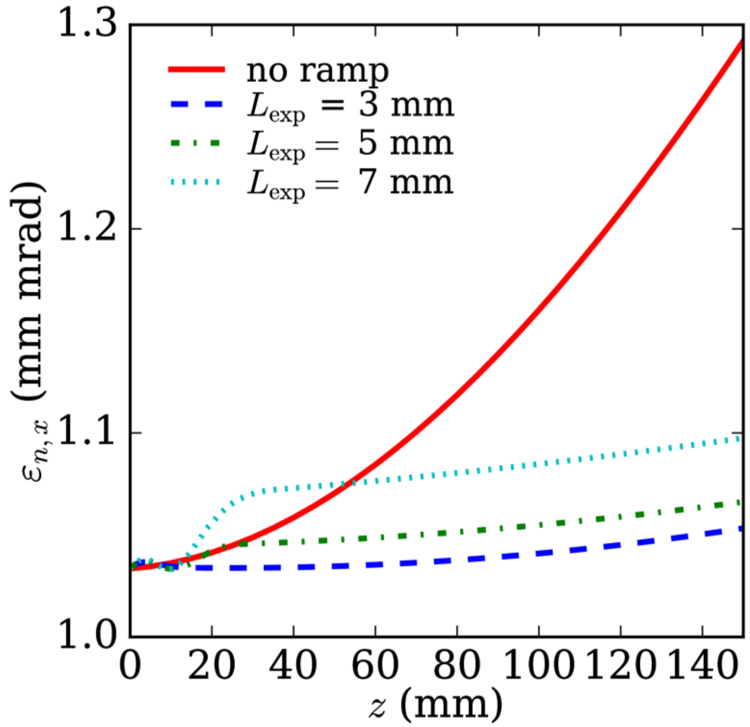
À noter : Un certain degré de sophistication est nécessaire !!

Injection, Extraction & Transport du faisceau

To minimize emittance growth, <u>it is imperative to</u>:

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





2 **Design transport lines where**
number of quadrupoles = number of constraints (as few quadrupoles as possible!)

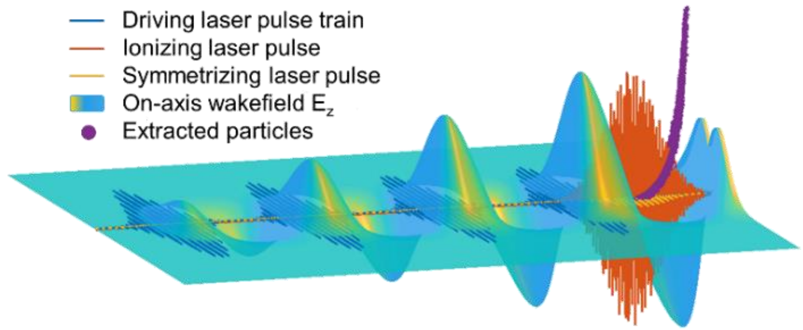
LETL: 1.2 m, HETL: 8 m, with places for diag. and a C-chicane for laser removing

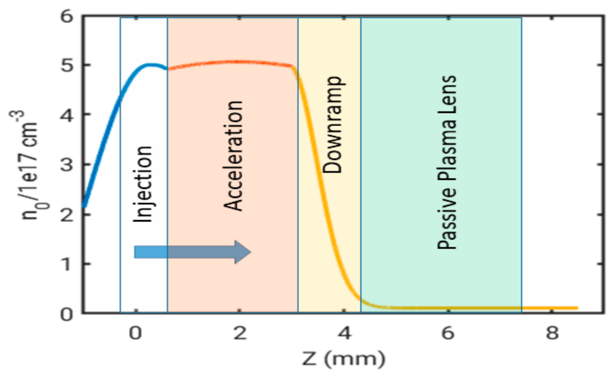
➔ 20% emittance growth through injection, acceleration, extraction and transfer to FEL users

Specifications for laser & plasma at 150 MeV

"ReMPI"

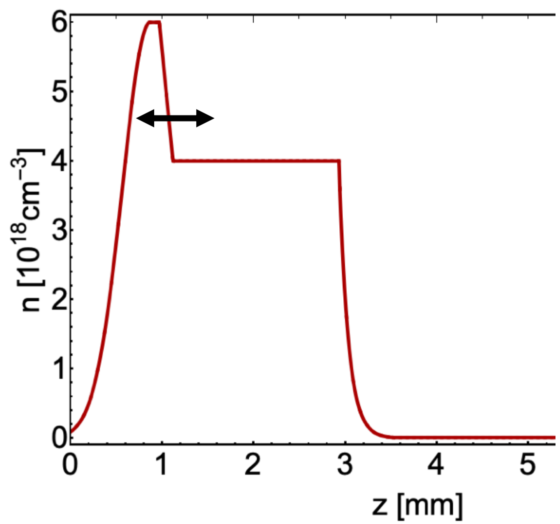
Driving laser: decomposed in 4 subpulses, delay 160 fs
120 TW, 4 J, $w_0 = 30\ \mu m$ ($a_0 = 1$, $\tau_{FWHM} = 30$ fs)
Ionizing laser: 3rd harmonic
1.0 TW, 0.07 J, $w_0 = 3.8\ \mu m$ ($a_0 = 0.53$, $\tau_{FWHM} = 45$ fs)
Symmetrization laser: 3rd harmonic, delay 40 fs
0.7 TW, 0.02 J, $w_0 = 11\ \mu m$ ($a_0 = 0.14$, $\tau_{FWHM} = 25$ 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, $w_0 = 18\ \mu m$ ($a_0 = 1.8$, $\tau_{FWHM} = 30$ 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 $n_0 = 1\ 10^{16}\ cm^{-3}$



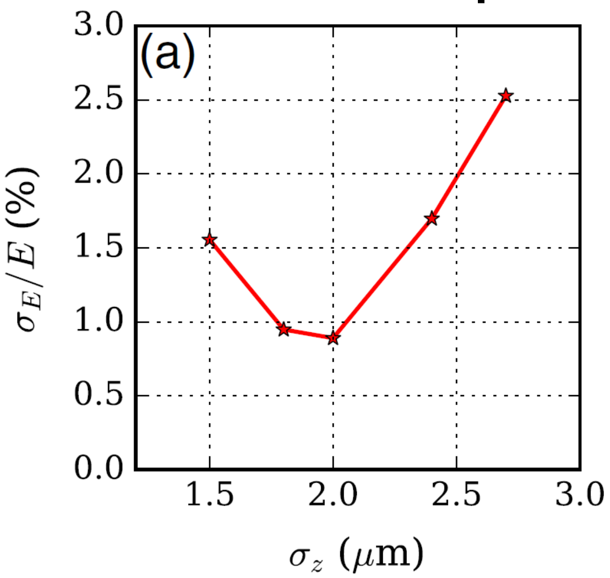
Spécifications for laser & plasma at 5 GeV

5 GeV

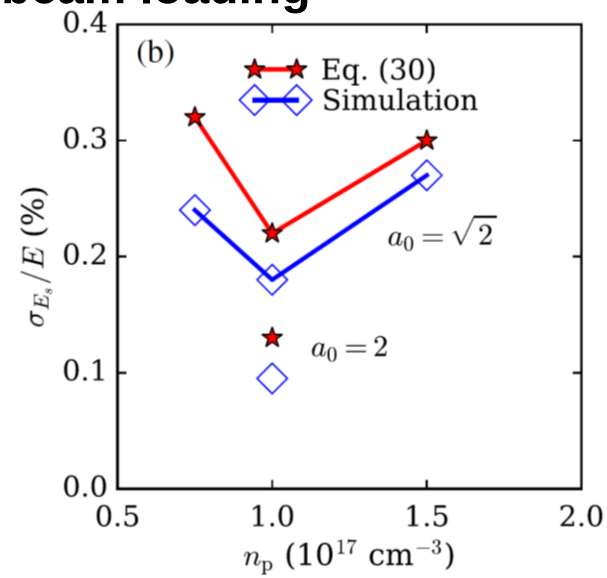
Laser: P = 400 TW, E = 60 J, w_0 = 45 μm (a_0 = 2.42, τ_{FWHM} = 141 fs)
Bi gaussian

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

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 & the laser strength

Summary

Un grand effort de simulations et d'optimisations
fourni par plus de 11 laboratoires européens

→ Beaucoup de résultats sur differents injection/acceleration schémas et techniques

→ Problèmes de préservation d'émittance entre étages plasma a été étudié et résolu

→ Simulations S2E faits de façon exhaustive

→ Paramètres faisceau chez les utilisateurs très proches des objectifs

Un certain degré de sophistication est nécessaire

Des solutions existent, et au moins une est robuste

D'autres schémas ou techniques restent prometteurs
Des progès sont encore possibles

En cours : Etudes des Erreurs et Tolérances