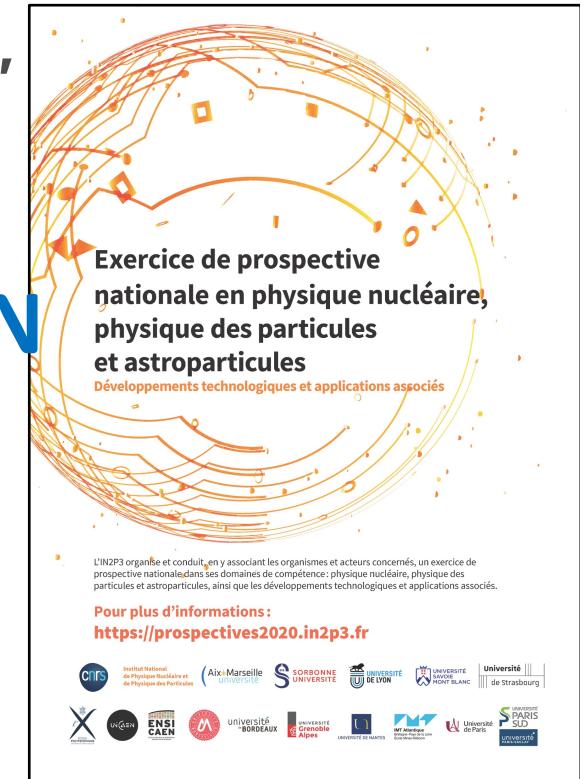


**Séminaire thématique**  
**GT07 "Accélérateurs et instrumentation associée"**

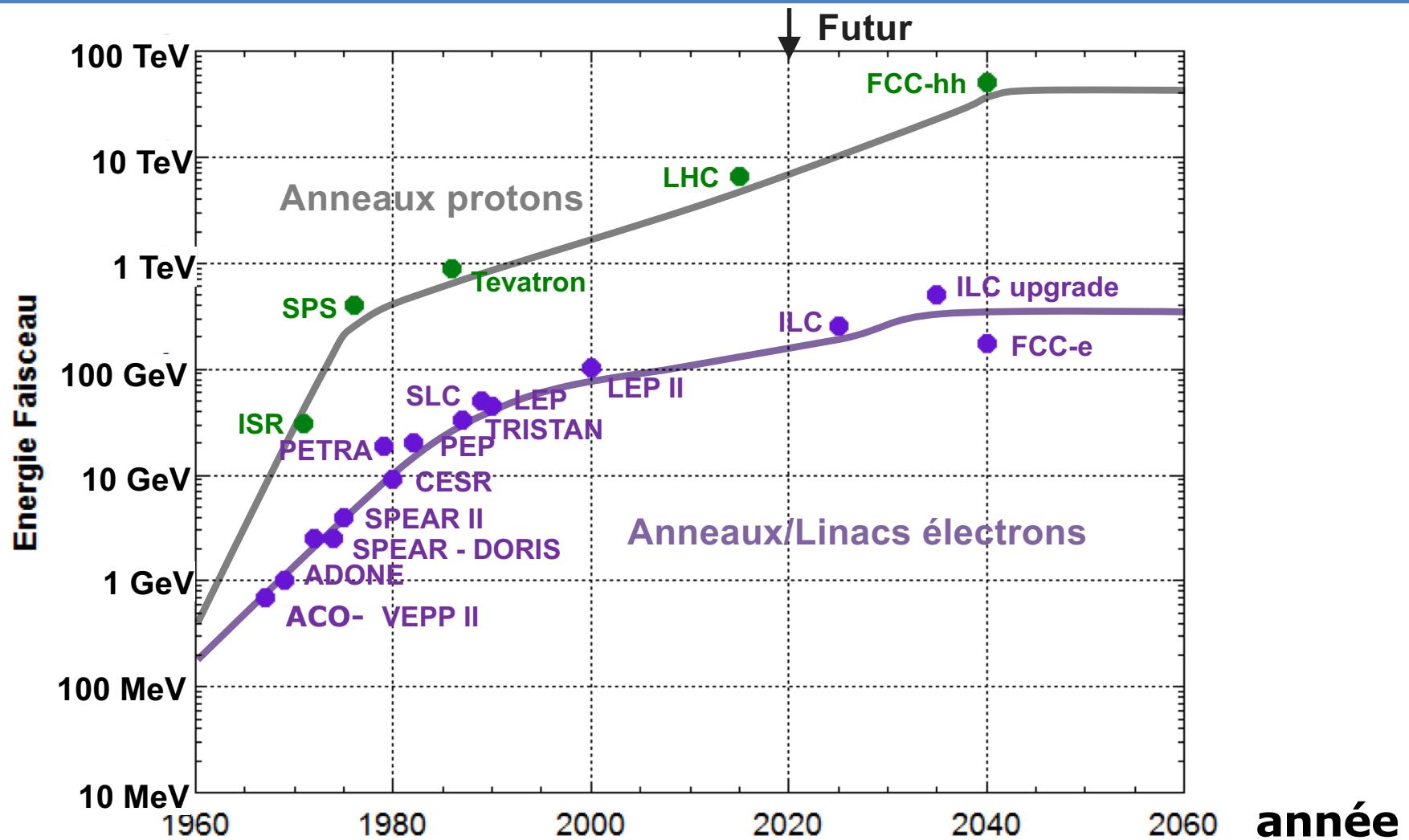
**Accélération Laser Plasma:**  
**- Accélération d'électrons sur APOLLON**  
**- Le projet EuPRAXIA**



Orateur: Arnd Specka

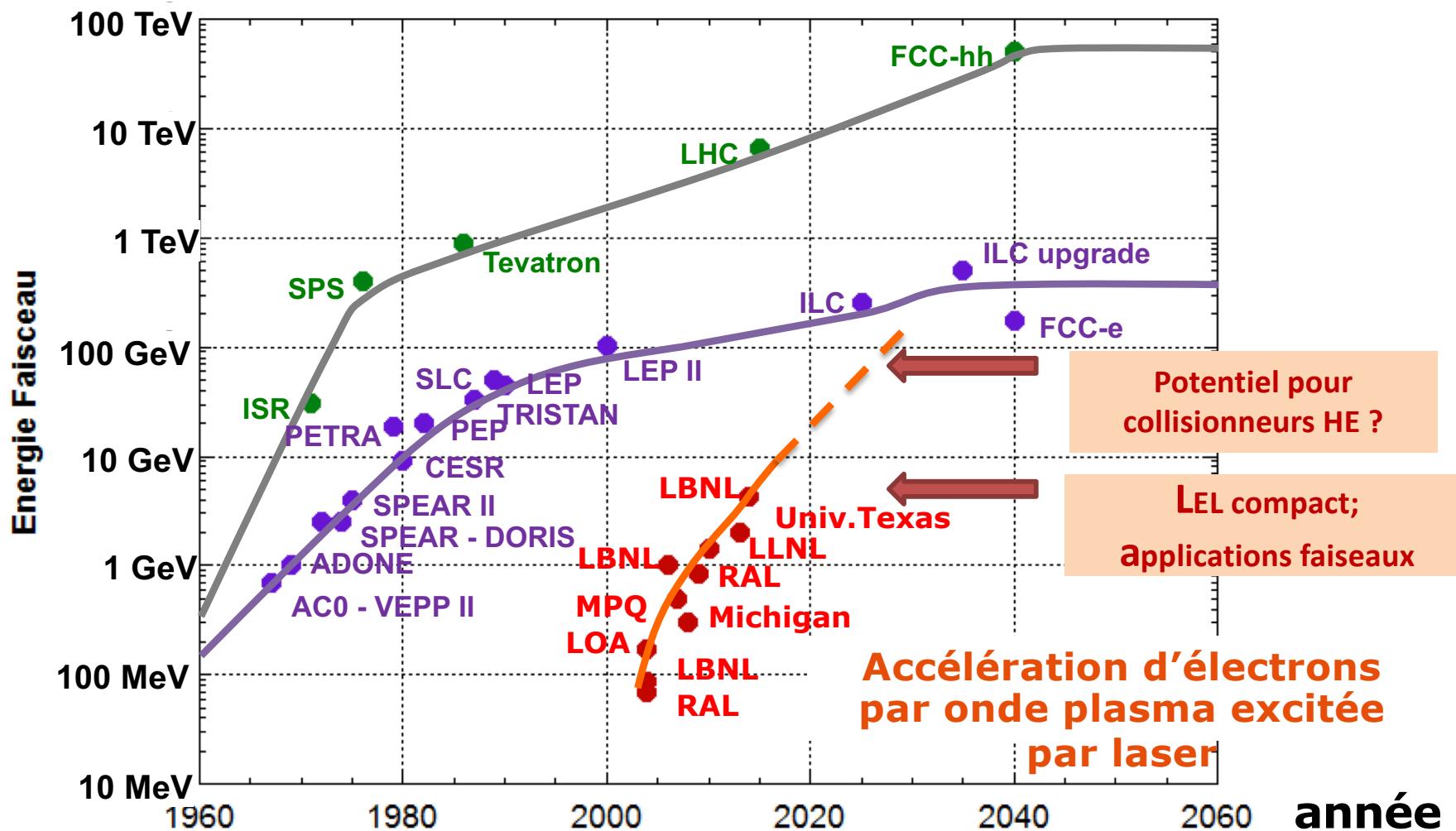
Contributions from: Ralph Aßman, Arnaud Beck, Antoine Chancé, Brigitte Cros, Nicolas Delerue, François Mathieu, Phi Nghiem, Julien Prudent, Sandrine Dobosz, Cédric Thaury, and many many more (apologies if your name is not here)

# Motivation: Evolution de l'énergie vs des collisionneurs e<sup>+</sup>/e<sup>-</sup> et p/p



- croissance en énergie → machines de plus en plus grandes
- longueur des LINACs déterminée par le gradient accélérateur

# Evolution des énergies obtenues en accélération laser-plasma



- gradients en ALP 10 à 100 fois supérieurs aux LINAC RF
- évolution des énergies maximales plus rapide

$$W = q \times E \times L$$

# Advanced and Novel Acceleration Techniques

- acceleration of electrons (and positrons)

drive beam	plasma medium	accelerating structure
e+/e-beam	plasma wakefield acceleration (PWFA*) <small>*) PWFA: historical misnomer</small>	dielectric structured wakefield acceleration (DSWFA)
proton beam	seeded self-modulation (SSM)	
<b>laser beam</b>	<b>laser wakefield acceleration (LWFA)</b>	dielectric laser acceleration (DLA)

- laser plasma acceleration of protons (and ions)

# Advanced and Novel Acceleration Techniques

- acceleration of electrons (and positrons)

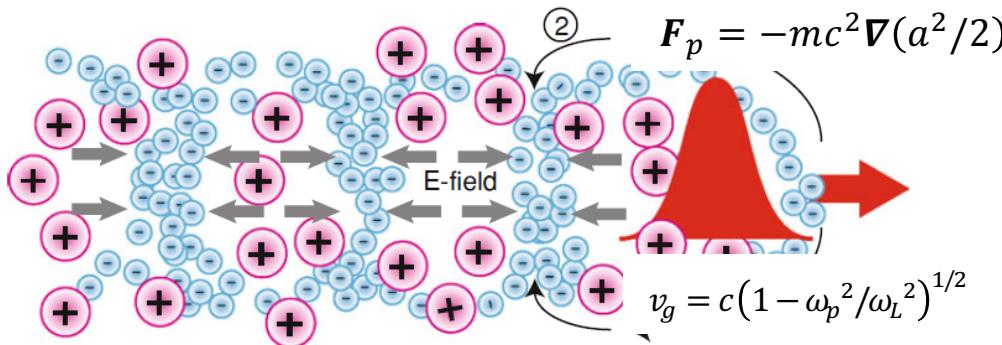
drive beam	plasma medium	accelerating structure
e+/e-beam	plasma wakefield acceleration (PWFA*) *) PWFA: historical misnomer	dielectric structured wakefield acceleration (DSWFA)
proton beam	seeded self-modulation (SSM)	
<b>laser beam</b>	<b>laser wakefield acceleration (LWFA)</b> <b>Arnaud Beck</b> <b>Kevin Cassou</b>	dielectric laser acceleration (DLA) <b>Jean-Luc Babigeon</b>

- laser plasma acceleration of protons (and ions) **Fazia Hannachi**

# Plasma wave driven by strong electric fields

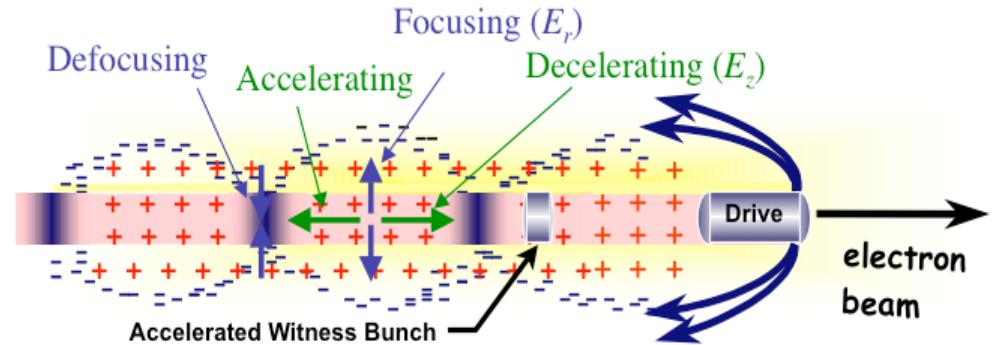
## laser field (vector potential $a$ )

T. Tajima & J.M. Dawson, Phys. Rev. Letter 43, 267 (1979)



## particle beam field

P. Chen & J.M. Dawson, AIP Conf Proc 130, 201 (1985)



1-D linear theory: plasma wave = forced electron density oscillation

1-D linear approximation  $a^2 \ll 1$

$$\left( \frac{\partial^2}{\partial \xi^2} + k_p^{-2} \right) \frac{\delta n}{n_0} = \nabla^2 \frac{a^2(\xi)}{2}$$

plasma wave    ponderomotive  
force

$$\xi = z - ct$$

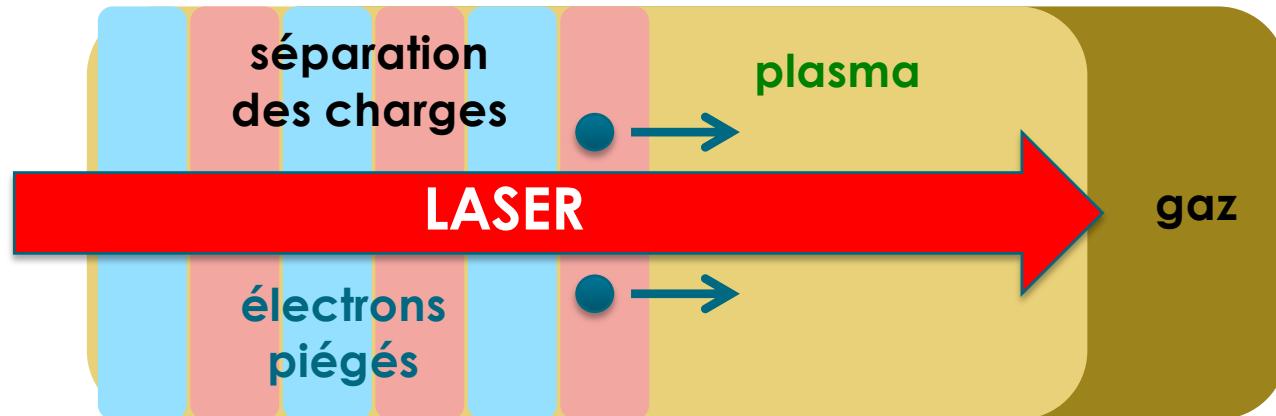
1-D linear approximation  $n_b/n_0 \ll 1$

$$\left( \frac{\partial^2}{\partial \xi^2} + k_p^{-2} \right) \frac{\delta n}{n_0} = -k_p^{-2} \frac{n_b}{n_0}$$

space  
charge force

# Principe physique d'accélération laser de particules ALP: électrons

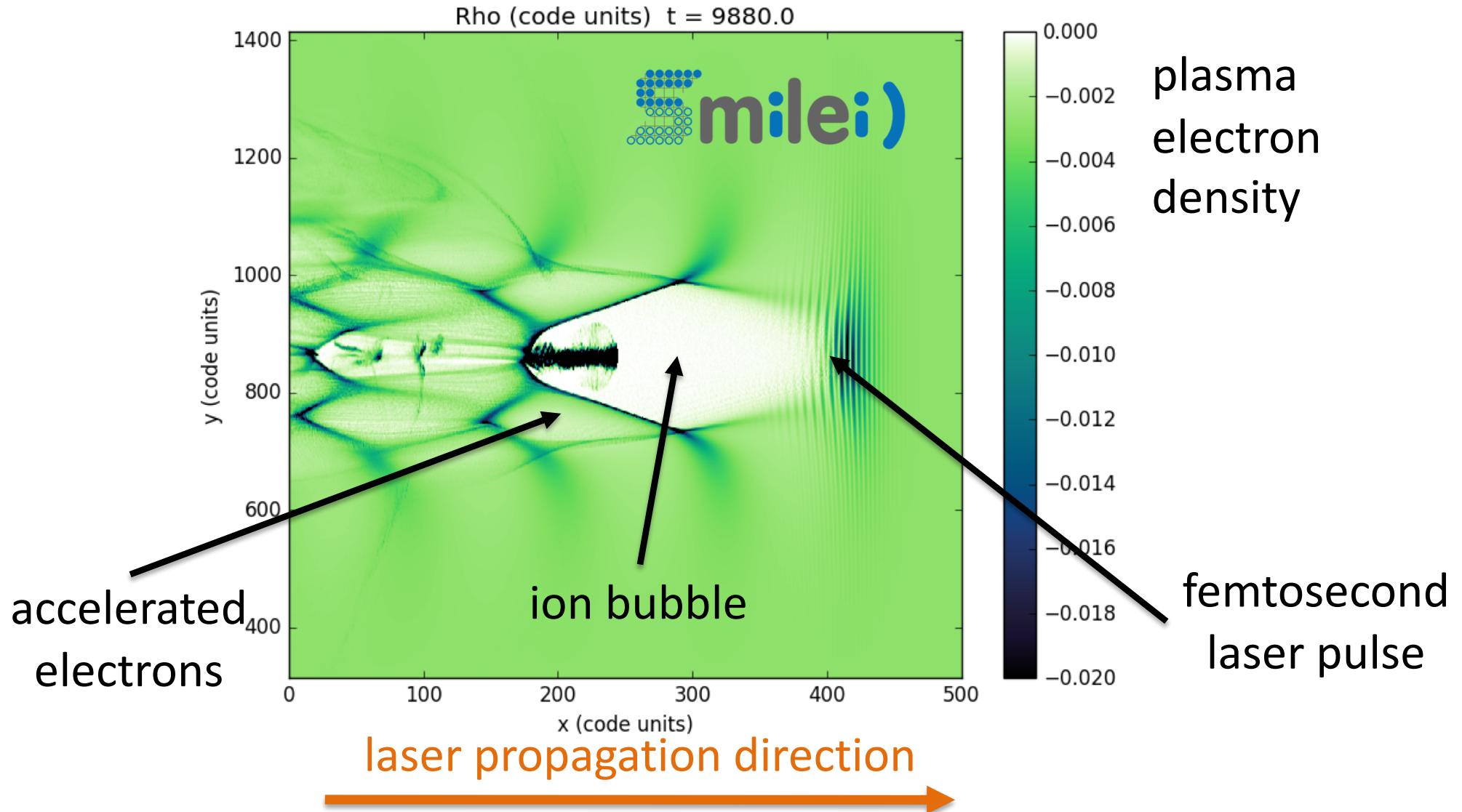
- laser de puissance à impulsion courtes: >50TW, 20-100fs, >1 J, focalisé



- accélération d'électrons: *laser wakefield acceleration (LWFA)*
  - cible gazeuse (plasma sous-dense)  
densité électronique:  $n_e \sim 10^{16} - 10^{19} \text{ cm}^{-3}$
  - ionisation par effet de champ
  - séparation des charges => onde plasma:  $\lambda_p \sim 300\mu\text{m} - 10\mu\text{m}$
  - $v_{PH}$  (onde) =  $v_G$  (laser) => onde relativiste

# Simulation of laser plasma acceleration in blowout regime

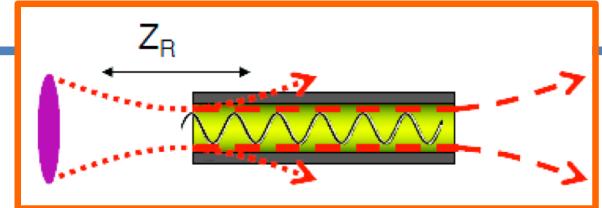
J. Derouillat et al., Comput. Phys. Commun. 222, 351-373 (2018)



# Accélération laser-plasma d'électrons : limitations

- Diffraction du laser: longueur de Rayleigh

- remède: (auto-focalisation), guidage par capillaire, décharge



- Déphasage du paquet et de l'onde plasma ( $\gamma_{el} > \gamma_{onde}$ )

$$L_{max} \propto n_0^{-3/2}$$

- remède : rampe de densité d'électrons décroissante, multi-étage

- Epuisement du laser (*depletion*)

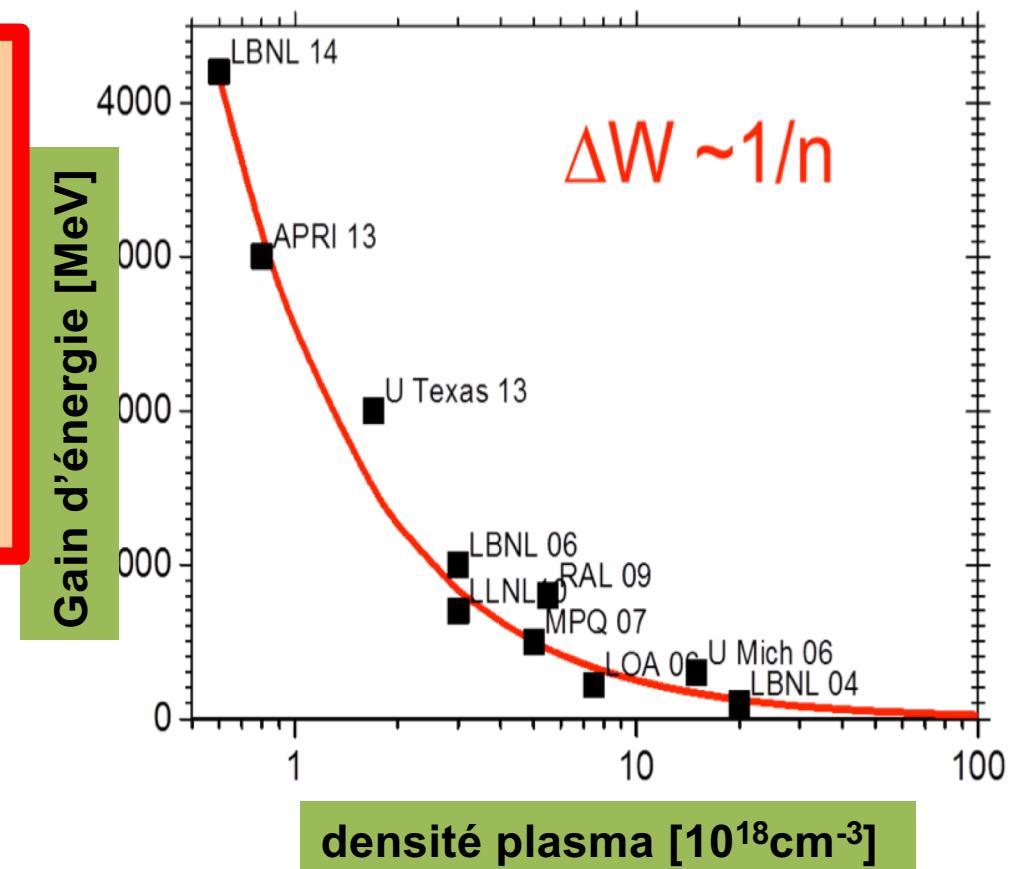
$$L_{deplete} \propto \lambda_p^3 / \lambda_L^2 \propto n_0^{-3/2}$$

- gradient acc.:  $G \sim E_0 = mc\omega_p/e \propto \sqrt{n_0}$

- gain d'énergie:  $W = G \times L_{acc} \propto 1/n_0$

- puissance crête laser:  $P_{laser} \propto 1/n_0$

augmenter le gain d'énergie (par étage)  
=> baisser la densité plasma  
et augmenter la puissance laser



# Current Status of LWFA Electron Bunch Properties

Property	State of Art*	Reference	Remarks
Energy	2 GeV ( $\pm 5\%$ , 0.1 nC) 3 GeV ( $\pm 15\%$ , $\sim 0.05$ nC) 4 GeV ( $\pm 5\%$ , 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) - LBNL	Accelerates from $E \approx 0$
Energy Spread	1% (@ .01 nC, 0.2 GeV) 5-10%	Rechatin (2009a) – LOA more typical, many results	0.1% desirable for FELs & colliders
Normalized Transverse emittance	$\sim 0.1 \pi \text{ mm-mrad}$	Geddes (2008) - LBNL Brunetti (2010) - Strathclyde Plateau (2012) - LBNL	Measurements at resolution limit
Bunch Duration	$\sim \text{few fs}$	Kaluza (2010) – Jena ( <a href="#">Faraday</a> ) Lundh (2011) – LOA; Heigoldt (2015) – MPQ/Oxford ( <a href="#">OTR</a> ) Zhang (2016) – Tsinghua	Measurements at resolution limit
Charge	0.02 nC @ 0.19 GeV $\pm 5\%$ 0.5 nC @ 0.25 GeV $\pm 14\%$	Rechatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: $Q/\Delta E$ ?
Repetition Rate & Repeatability	$\sim 1 \text{ Hz}$ @ $> 1 \text{ GeV}$ $1 \text{ kHz}$ @ $\sim 1 \text{ MeV}$	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénnot ('17) -- LOA	Limited by lasers & gas targets

- \* No one achieves all of these simultaneously!

- Couperus, *submitted* ('17)
- Geddes, *PRL* **100**, 215004 ('08)
- He, *Nat. Comms* **6**, 7156 (2015)

- Heigoldt, *PR-STAB* **18**, 121302 ('15)
- Kaluza, *PRL* **105**, 115002 ('10)
- Kim, *PRL* **111**, 165002 (2013)

- Rechatin, *PRL* **103**, 194804 ('09b)
- Leemans, *PRL* **113**, 245002 (2014)
- Lundh, *Nat. Phys.* **7**, 219 (2011)
- Rechatin, *PRL* **102**, 164801 (2009)
- Salehi, *Opt. Lett.* **42**, 215 ('17)
- Wang, *Nat. Comms* **4**, 1988 (2013)
- Zhang, *PRST-AB* **19**, 062802 (2016)

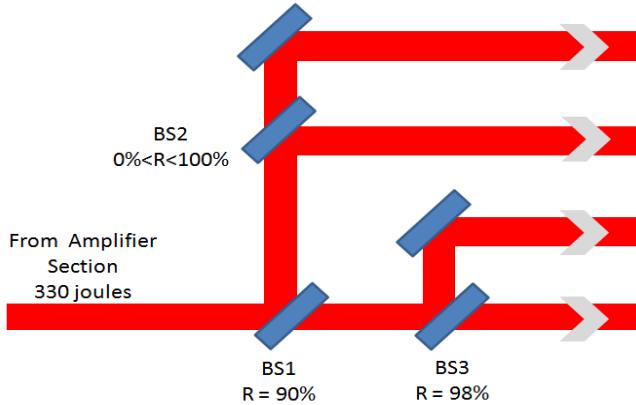
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## **Expériences d'accélération d'électrons sur APOLLON**

# Le laser de puissance APOLLON

- CPER ILE + Equipex CILEX + ... =>  
LASER APOLLON + 2 salles expérimentales équipées (15M€)

- 4 faisceaux indépendants, énergies variable



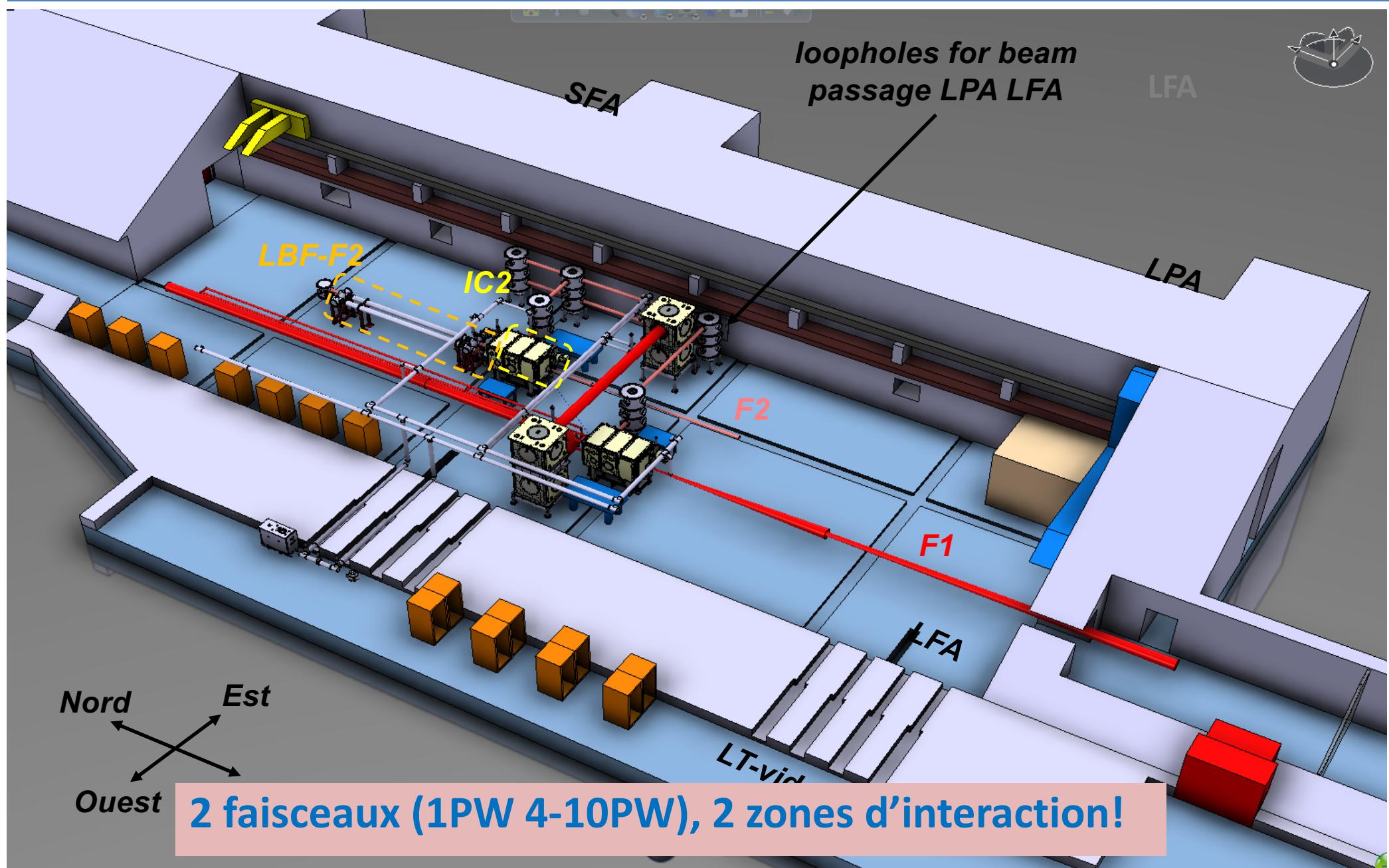
- Salle longue focale (LFA): acc. électrons
- Salle courte focale (SFA): acc. protons

uses CPA (Chirped Pulse Amplification), Nobel Prize 2018

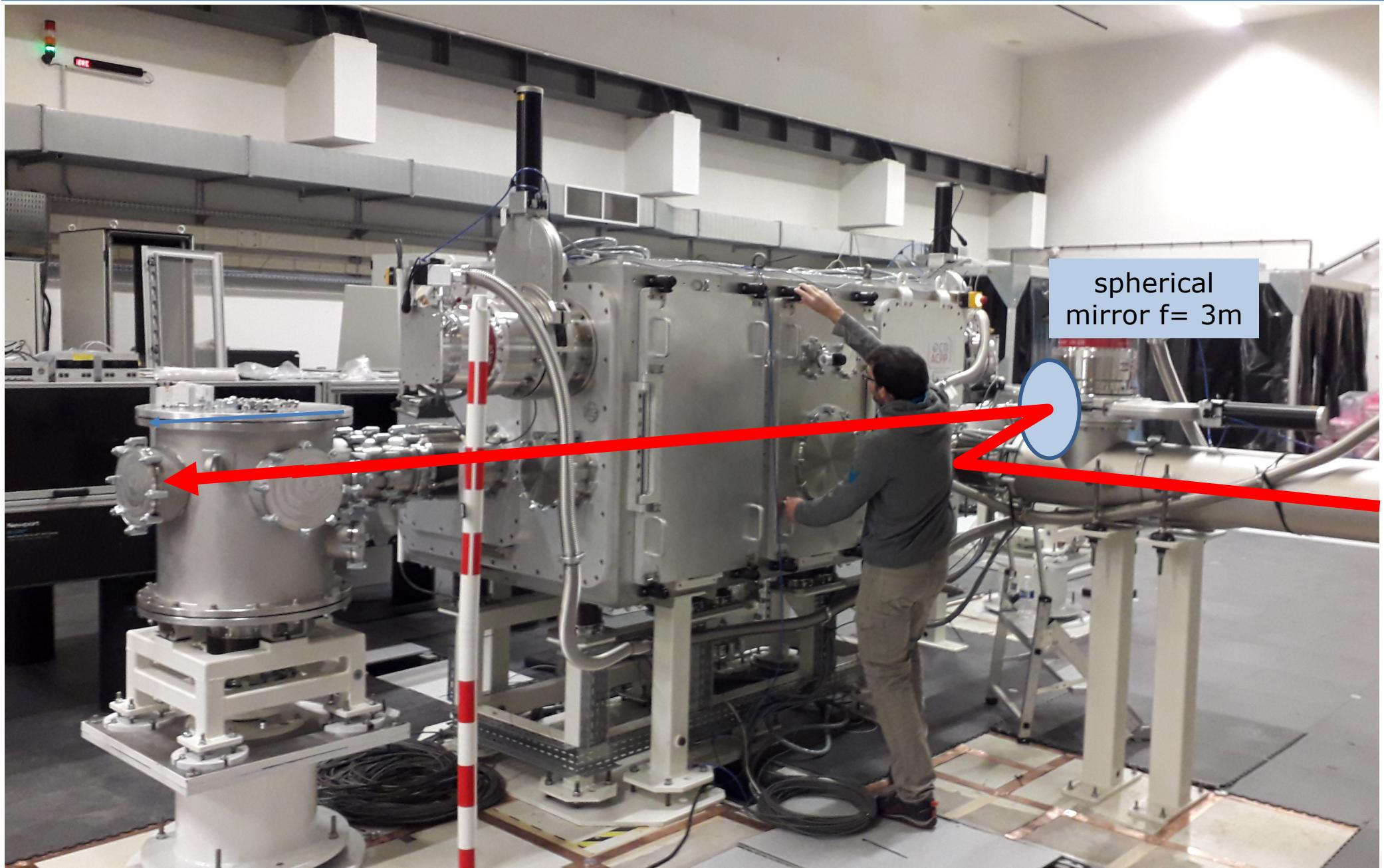
- Stabilité du pointé (angle)
- Synchronisation des faisceaux
- «haute» cadence : 1 tir/min



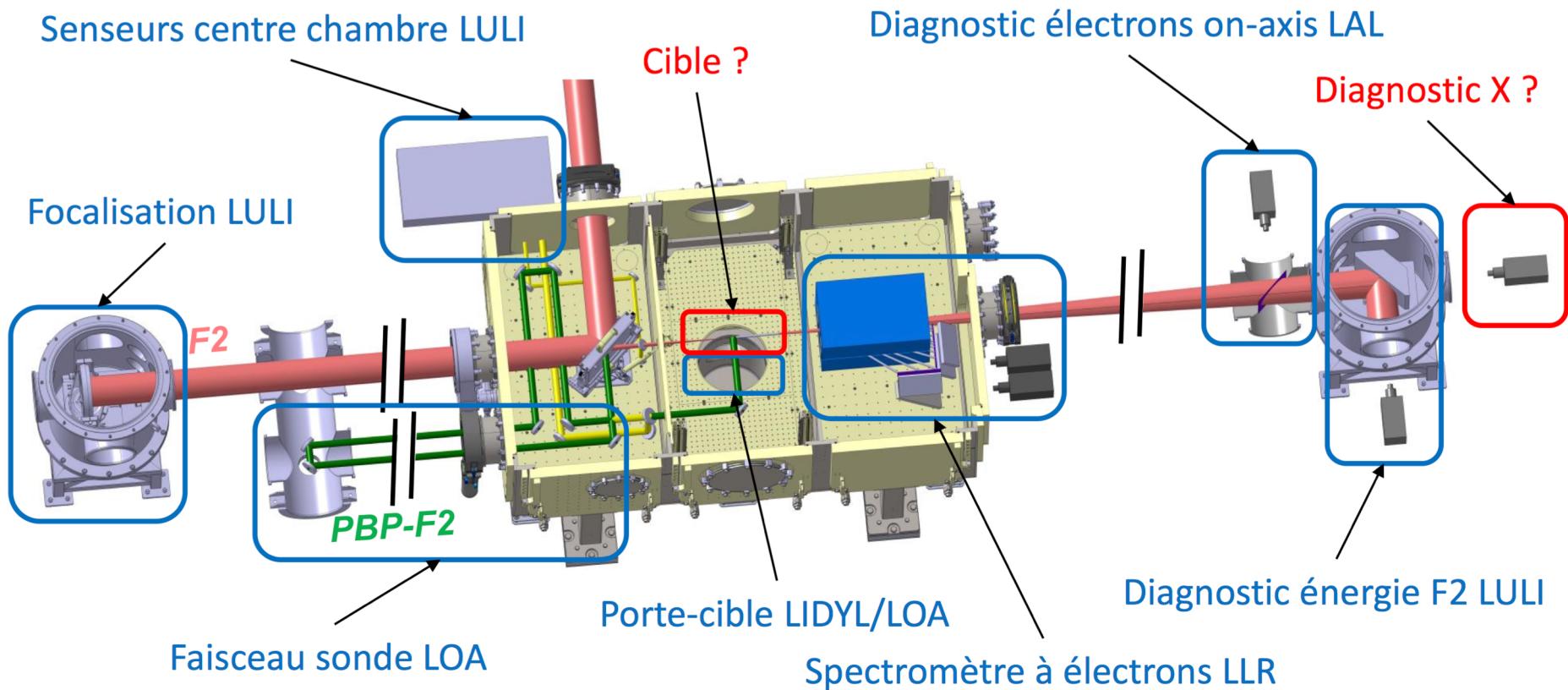
# Long Focal Area (electron acceleration)



# Preparation of 1<sup>st</sup> e<sup>-</sup> acceleration experiment at APOLLON 1PW



# First experiments on CILEX-APOLLON 1PW Laser



2020: « qualification experiments »: demonstrate laser capabilities

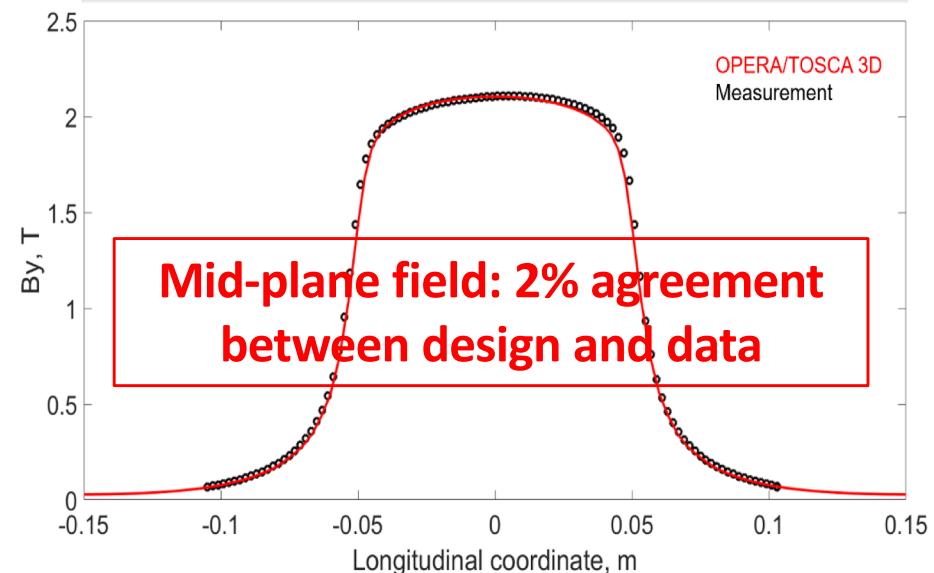
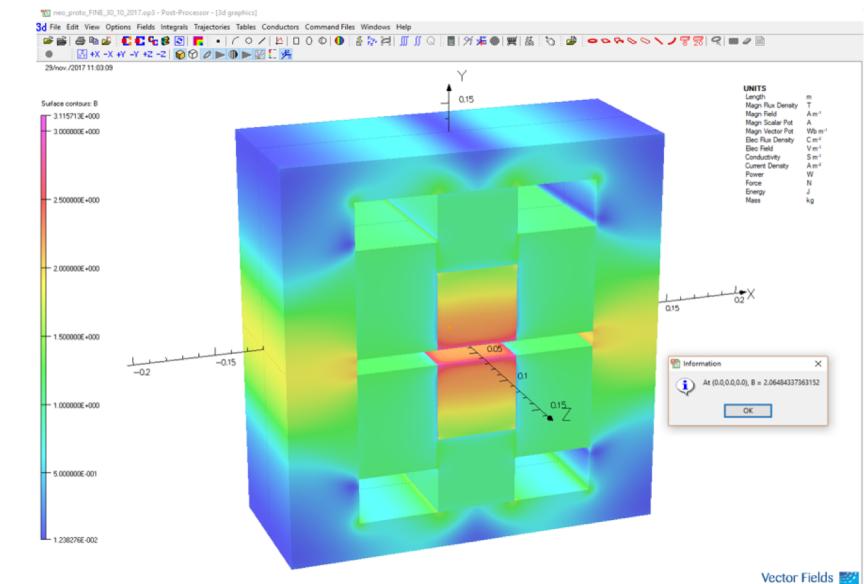
2021: Target 1 of CILEX scientific program: bubble regime w/ 1 beam

## 2.1 Tesla permanent dipole magnet (2017) LLR

spectrometer for APOLLON 1PW  
energy range: 200 – 2000 MeV



M.Kojoyan et al., ICAP 2018 Proceedings, JACoW  
M.Kojoyan et al., IBIC 2018 Proceedings, JACoW



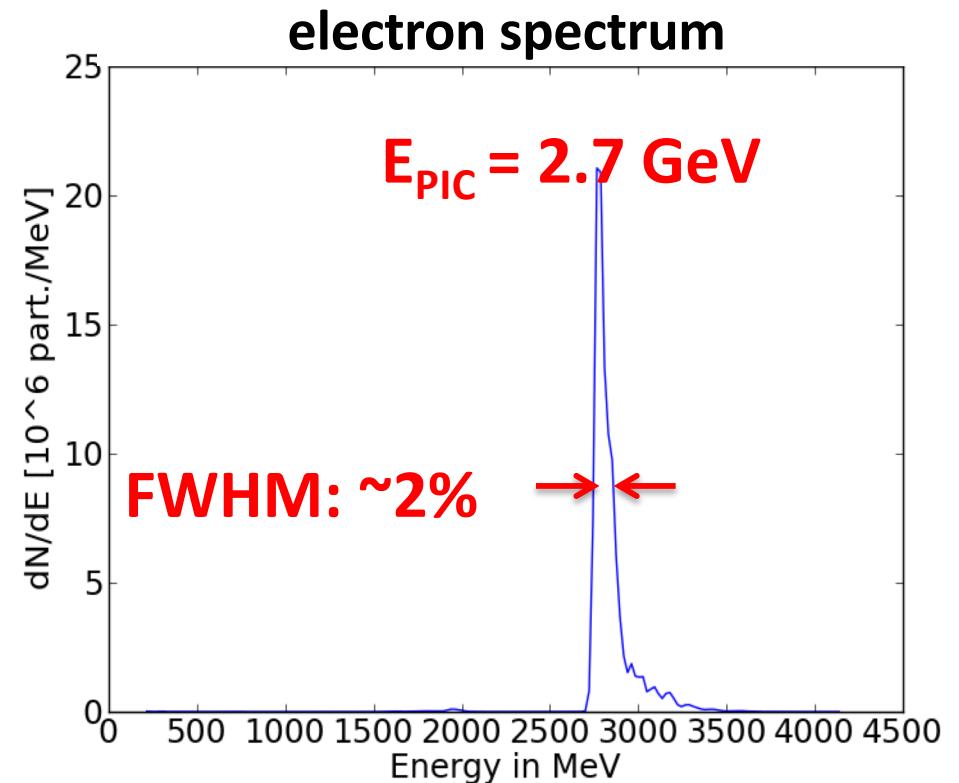
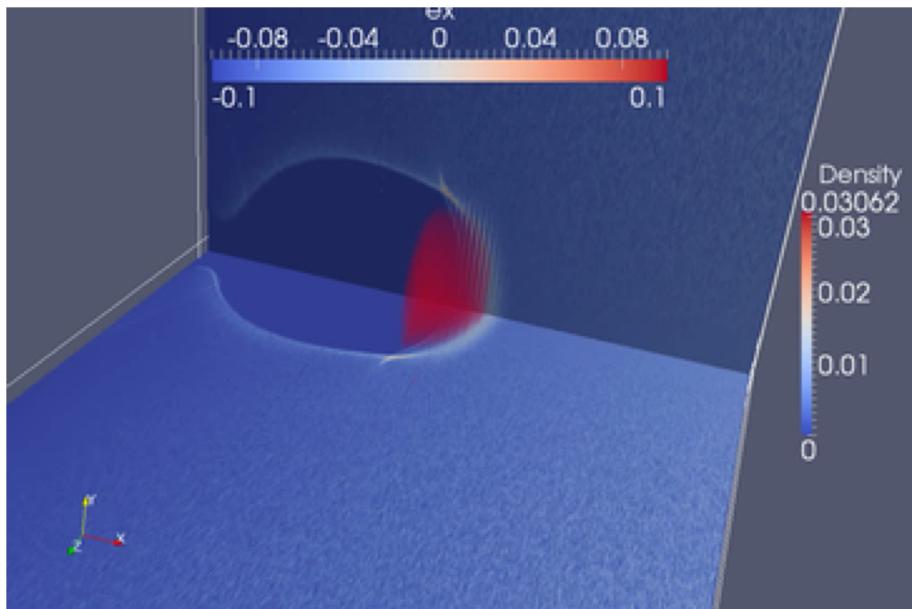
## CILEX-APOLLON scientific advisory committee 2015

- T1. Exploratory experiments using a single beam
  - Validate scaling laws & commission the facility (laser parameters, experimental area)
  - Explore new regimes to produce high quality electron beams in the few GeV range
- T2. Optimize injector (1PW):
  - >100pC charge electron bunches in the range 50-300MeV, that can be focused at the entrance of the 2<sup>nd</sup> stage.
- T3. Develop and implement the equipments necessary to
  - Characterize electron bunches (energy and spatial distribution)
  - Synchronize electron bunch and laser beam
  - Transport electron bunches at the entrance of the second stage
  - Guide the laser beam over large distances (0.1-1 m)

# CILEX-APOLLON: simulation of first experiments

- self injection of plasma & non-linear blowout regime
- Laser 800nm, 15J, 25fs (600TW, APOLLON 1PW startup)

ion bubble shrinks, then expands



- stable acceleration over « long distances without laser guiding
- energy spectrum peaks around ~3 GeV after ~20mm propagation

A. Beck et al., Nucl.Instrum.Meth. A740 (2014) 67-73.

# APOLLON: Calendrier et fonctionnement envisagé

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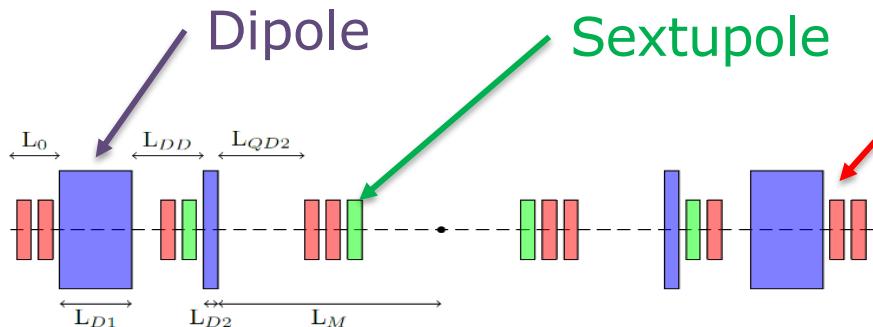
*Etat du 01/2020:*

*En attendant l'autorisation de l'ASN: qualification du laser et préparation des 1ères expériences (instrumentation + simulation)*

- avant 2019 : partenaires «CILEX »: LULI, LAL, LPGP, LLR, LOA, SOLEIL participent à la construction de l'installation
- 2019: installation expériences LPA en salle longue focale qualification du laser 15J (sans plasma)
- 2020: APOLLON devient un IR (CNRS&Ecole Polytechnique)
- 2020: 4 campagnes (à 2 semaines) de qualification (dont 2 en salle longue focale = accélération d'électrons)
- 2021: ouverture progressive, beamtime via PAC
- 2021-2025: 20% du temps faisceau for project partners
- 2022-2023: commissioning du laser multi-PW (4PW)



# Multistage @ CILEX: Simulations



Quadrupole

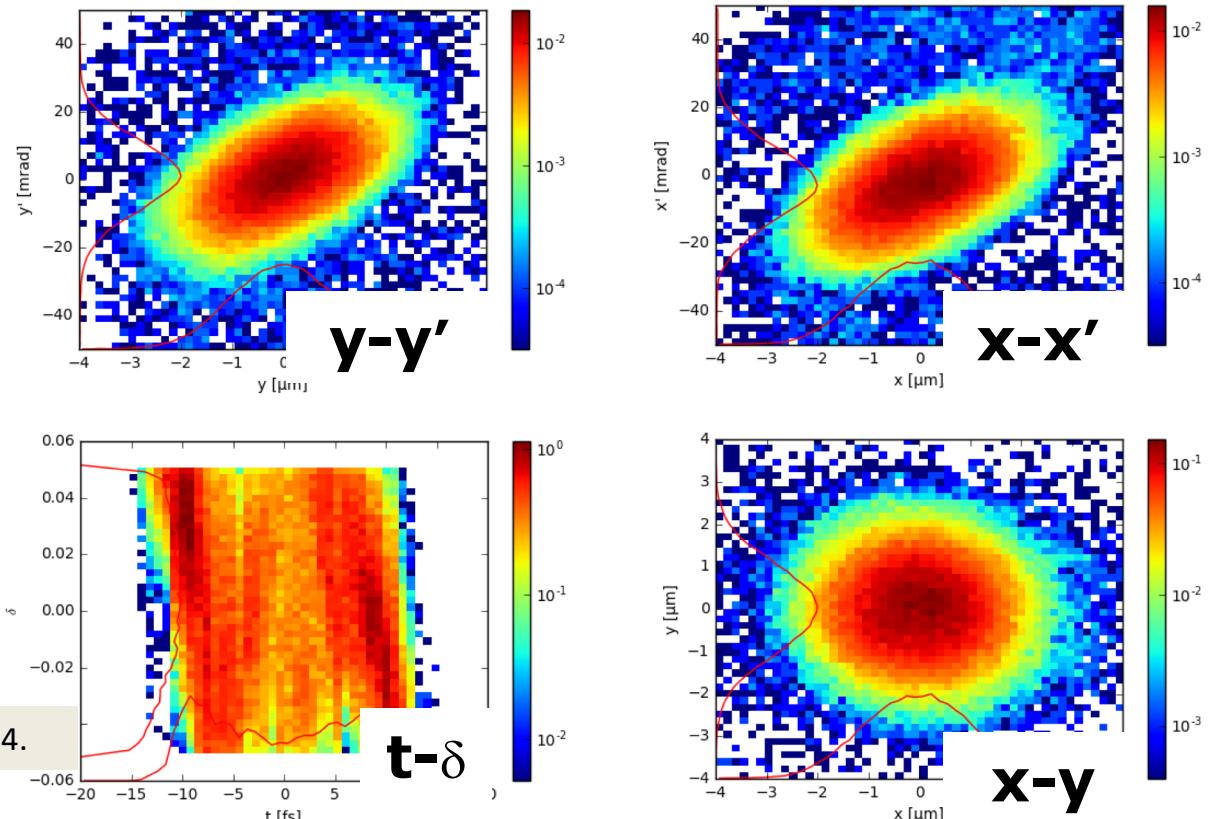
Courtesy: A. Beck (LLR)

Simulation results with Smilei

Eref = 200 MeV, Cut at +/- 10 MeV (5%)

$\varepsilon_{Nx} = 5.8 \mu\text{m}$ ,  $\varepsilon_{Ny} = 4.7 \mu\text{m}$ , charge:a few pC

- Initial distribution from PIC simulations (200 MeV)
- Tracking studies
- Start-to-end simulations can be performed
- beam line to be built by CEA/IRFU in ARIES



A. Chancé et al., Nucl.Instrum.Meth. A740 (2014) 158-164.

## Quelques « attendus » proposés (Brigitte Cros et al.)

---

- Démonstration de sources d'électrons laser plasma 150-300MeV  
2020-2022 LIDYL-LPGP : **515 keuros**
- Démonstration de sources d'électron laser plasma jusqu'à quelques GeV  
2020-2025 LIDYL: **180 keuros**
- Stabilisation des paramètres du faisceau laser et des paramètres 2020- 2022, LULI  
: **330 keuros**
- Conception et construction de la ligne de transport et focalisation  
2020-2022
- Milieux plasmas long pour le guidage laser et l'accélération d'électrons  
2020-2022 : LPGP : **949 keuros**
- diagnostics monocoups de caractérisation et de synchronisation des faisceaux  
2020-2023 LAL : **727 keuros**
- démonstration d'applications en collaboration avec partenaires F ou européens.
- Accélération multi-GeV d'électrons externes dans l'étage plasma

## Conclusion: APOLLON

---

APOLLON sera le laser de puissance en France qui permettra de produire des électrons multi-GeV aisément

- démarrage d'expériences d'APOLLON en 2020 espéré
- programme doit être adapté en fonction des performances
- les équipes travaillant sur l'ALP d' $e^-$  bien placées pour mettre à profit le 20% du temps dédié.  
=> la fédération des équipes doit continuer et être renforcée
- grande visibilité des résultats attendue
- exploration des applications possible, leur exploitation sera difficile
- « Le fonctionnement de l'installation Apollon comme installation laser ouverte aux utilisateurs ne permettra pas d'optimiser le fonctionnement d'un accélérateur. Cependant c'est une installation très attractive pour des collaborateurs extérieurs, qui permettra d'attirer des compétences supplémentaires à celles de la communauté française. »

EUROPEAN  
PLASMA RESEARCH  
ACCELERATOR WITH  
EXCELLENCE IN  
APPLICATIONS



*Le projet EuPRAXIA:  
Un accélérateur plasma pour la  
recherche et les application pilotes*



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

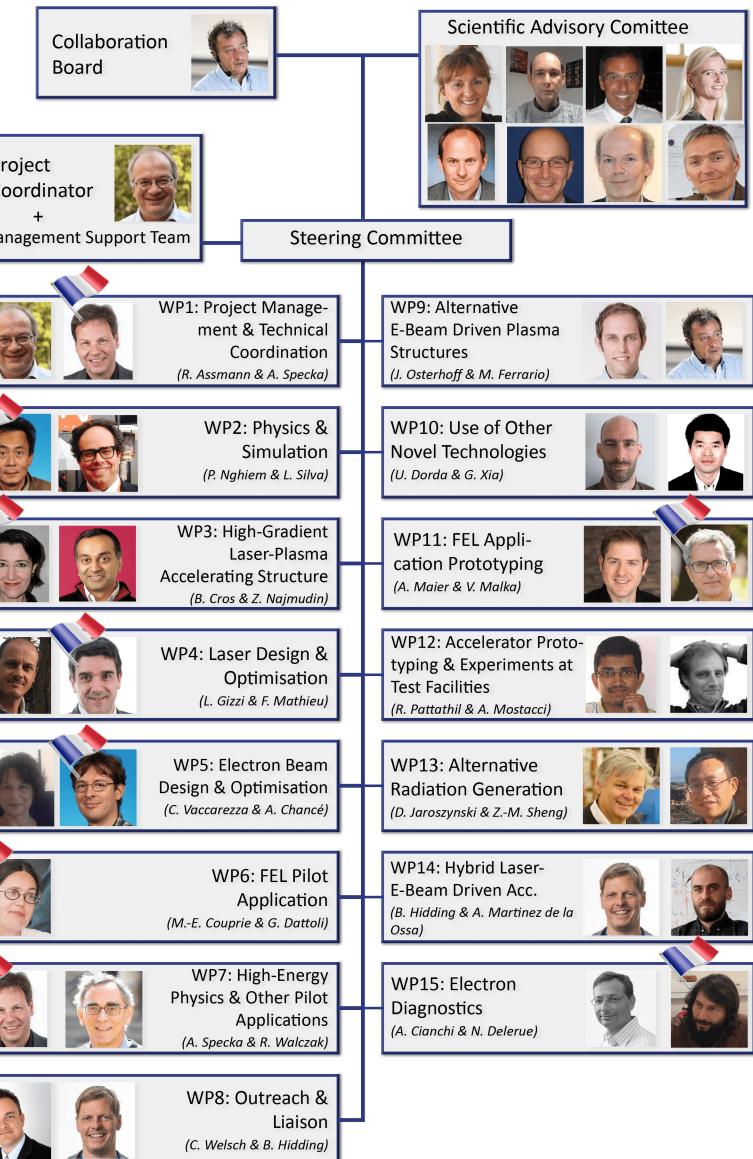
Diapositives courtesy of :  
**Ralph Assmann (DESY)**  
**coordinateur design study EuPRAXIA**

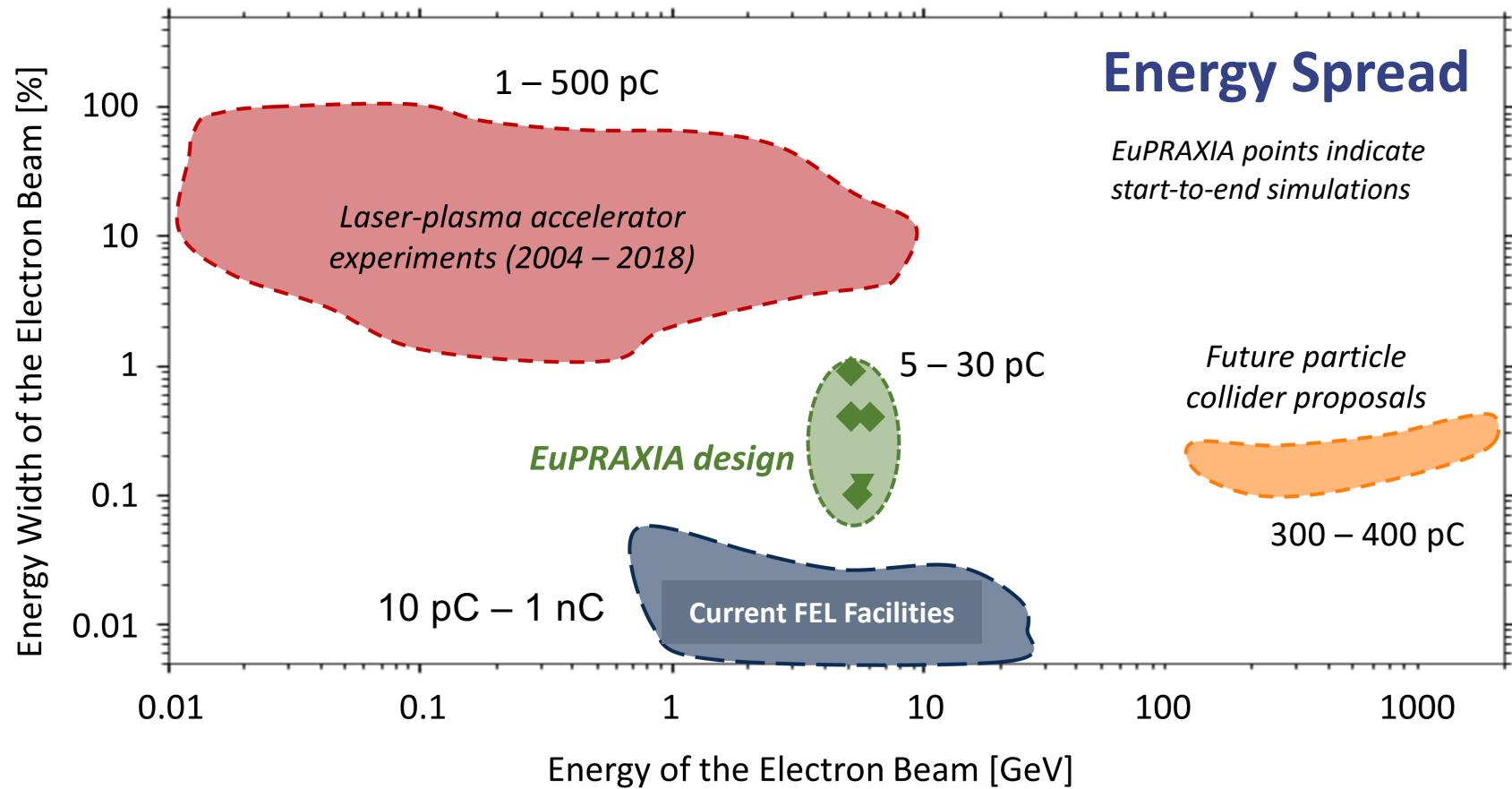
**EU funded Consortium (3 M€) to produce a CDR for a Euro Infrastructure 2016-2019**

- EU design study in 4<sup>th</sup> and final year:  
**16 beneficiaries, 25 associated partners, 15 Work Packages, 30 WP Leaders, more than 200 scientists contributed**
- One of four DS's in physical science approved in H2020. Others: EuroCirCol (FCC), CompactLight (X band), Neutrino (ESS)
- French WP (co) leaders for all central WP

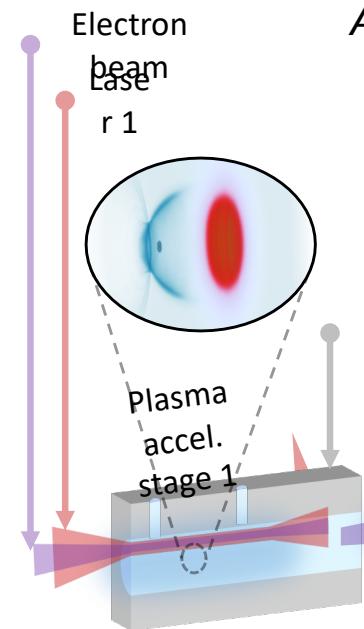


**Main deliverable:  
CDR published in 2019  
555 pages**

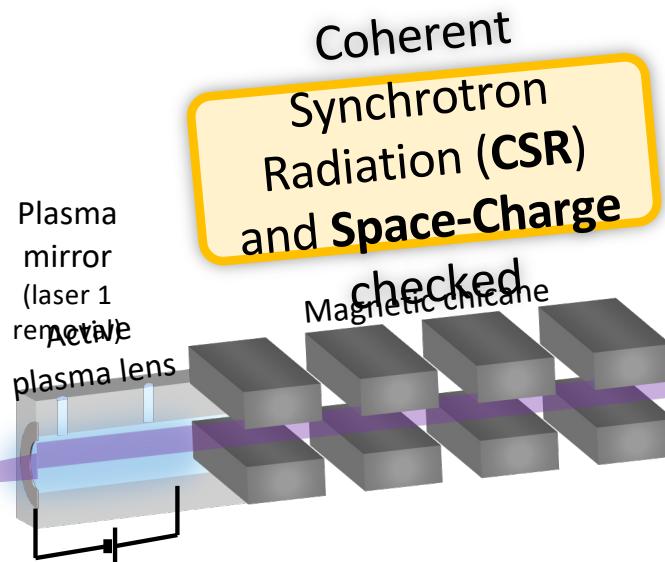




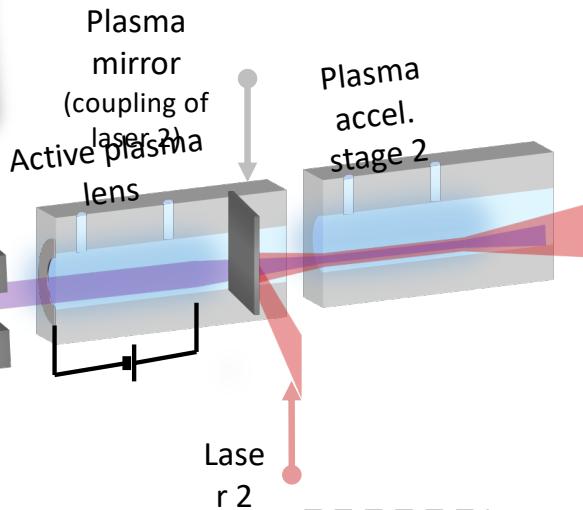
# Compact Multi-Stage Plasma-Based Accelerator



*Ángel Ferran Pousa et al*

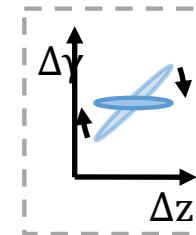
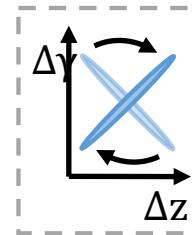
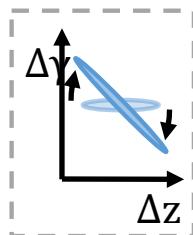


Not to scale. **Compact**  
setup  $\sim 1.5$  m.

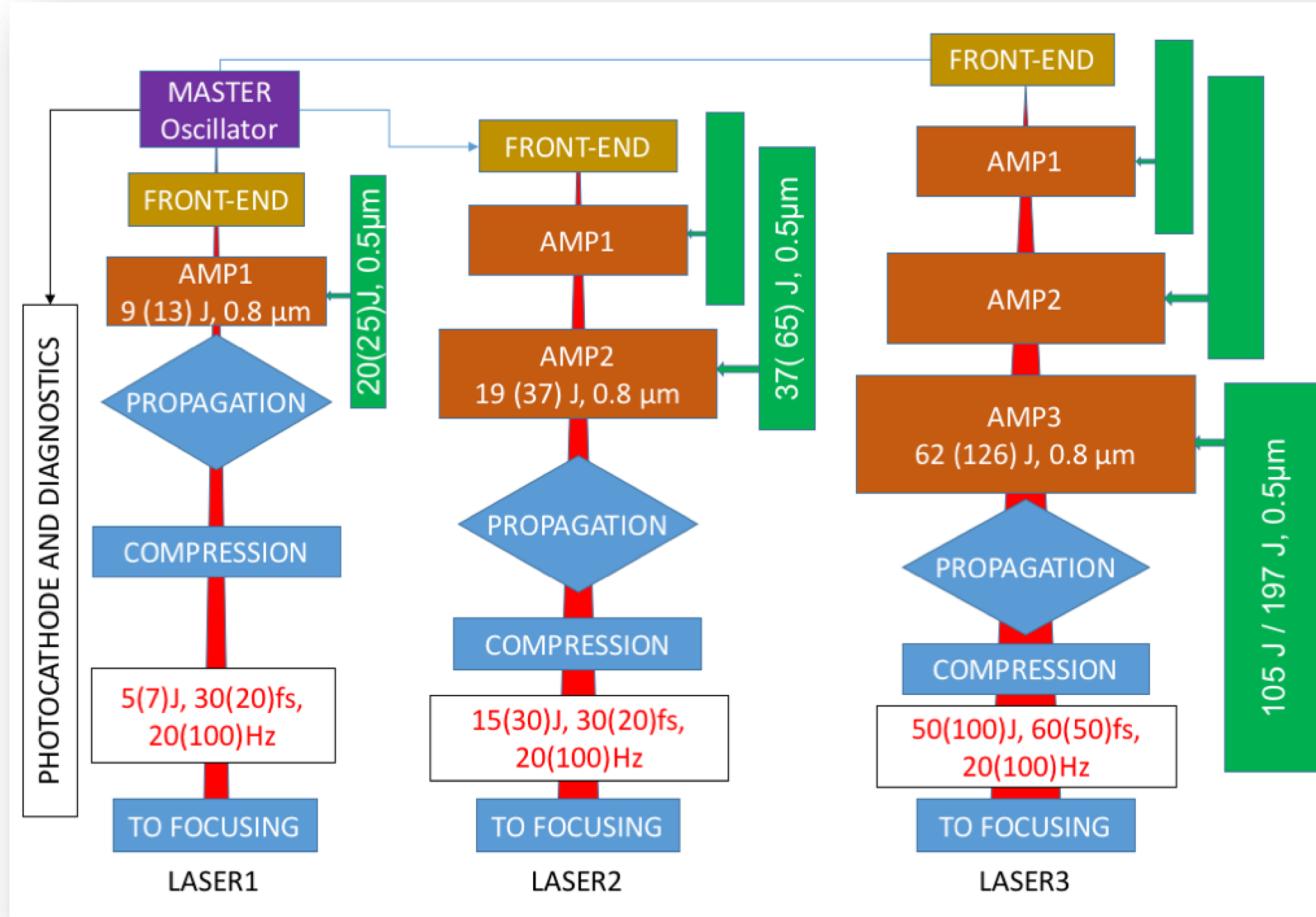


Combined RF plus  
optical scheme

- 1.5 m long
- 5.5 GeV
- **0.03%** slice energy spread
- **0.12 %** total energy spread
- sub-micron emittance

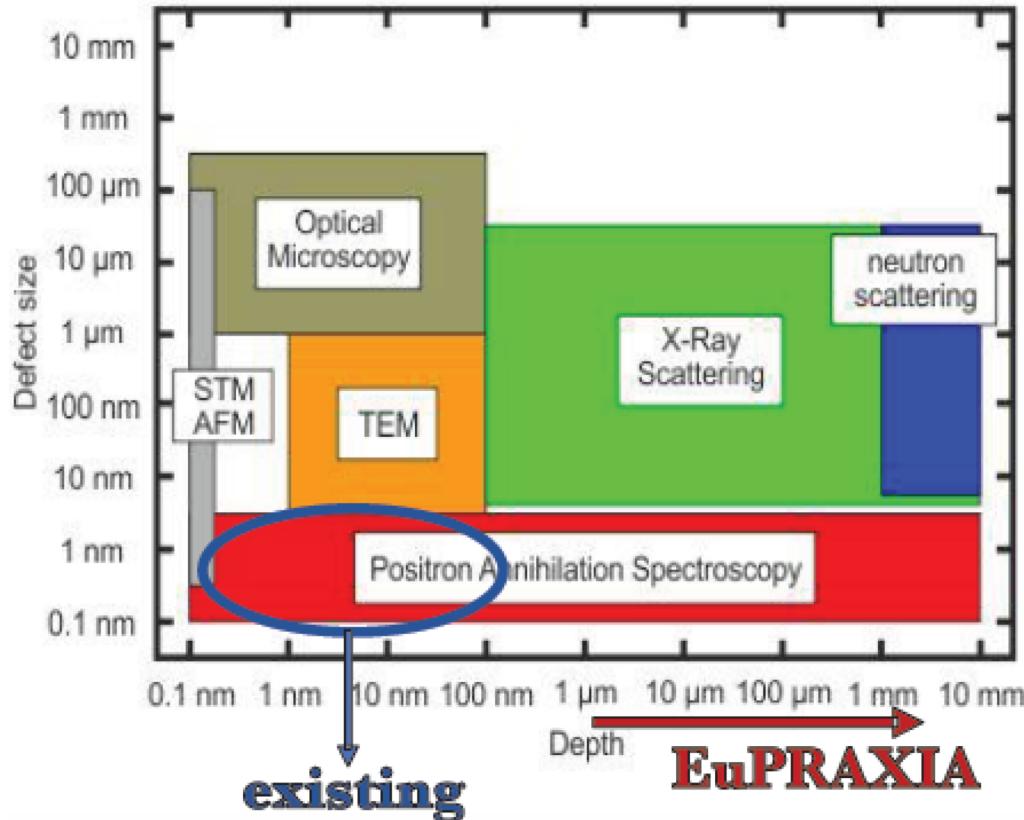


## EuPRAXIA Design: 20 – 100 Hz Lasers



- **Three laser systems** for the laser-driven plasma accelerator facility
- Baseline: Start from lasers at present **state-of-the-art**, however, extended to 20 Hz and then to 100 Hz
- In parallel: **Development** of high efficiency, high average power lasers

Leo Gizzi, Francois Mathieu et al



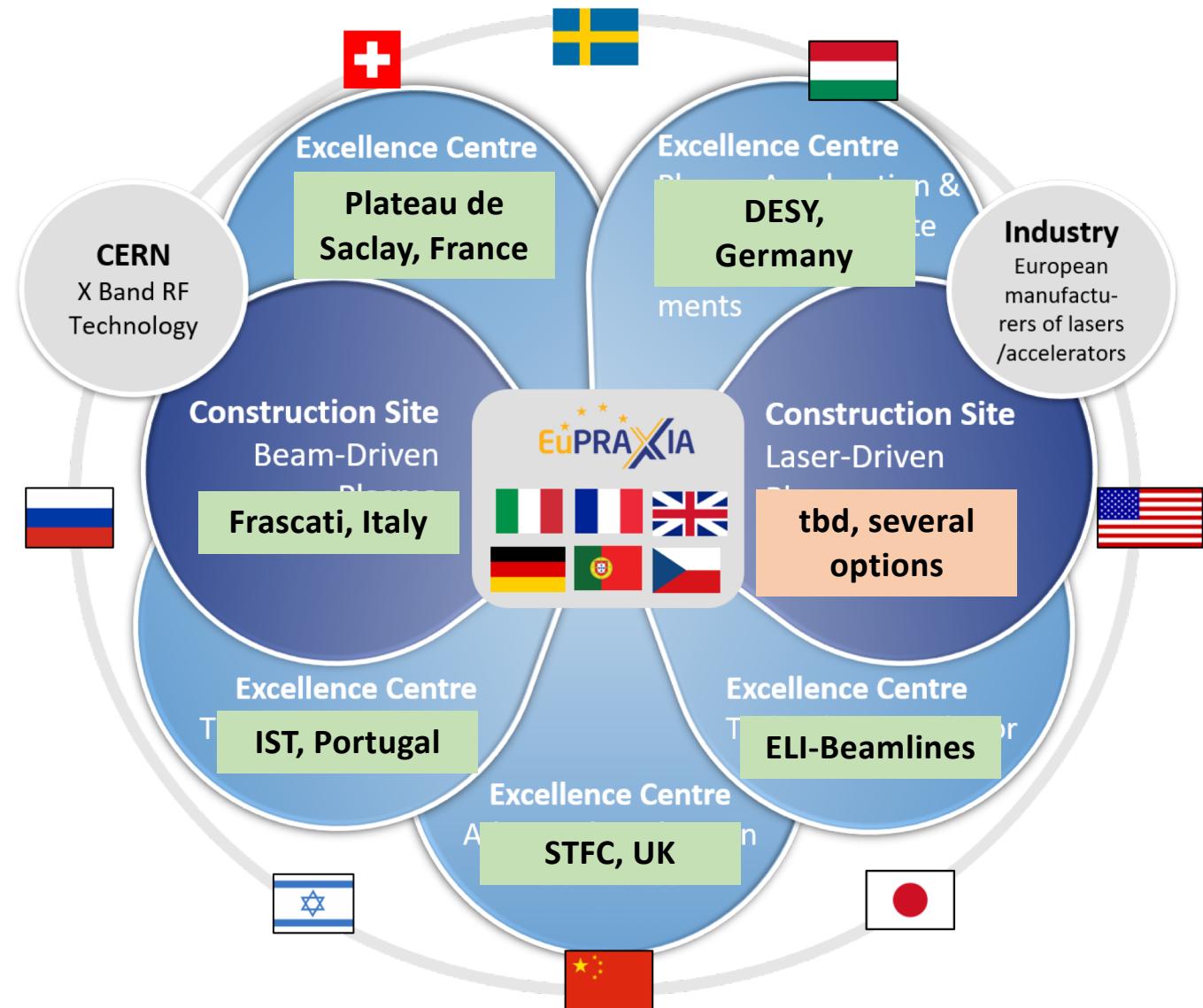
Quantity	Baseline Value
<b>Low-Energy Positron Source</b>	
Positron energy	0.5–10 MeV (tunable)
Energy bandwidth	±50 keV
Beam duration	20–90 ps
Beam size at user area	2–5 mm
Positrons per shot	$\geq 10^6$

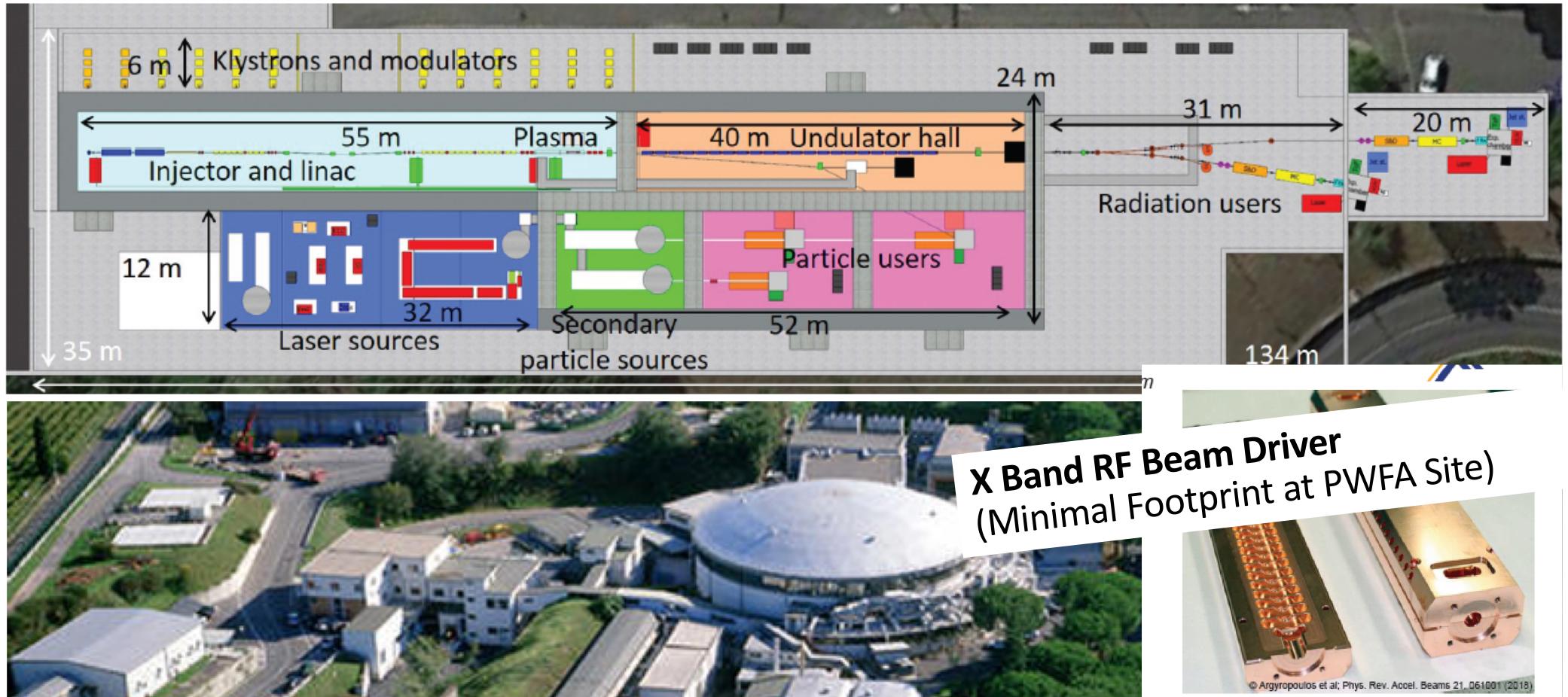
- EuPRAXIA would provide access to unique regime of detecting small defects at large penetration depths
- Does not require highest quality of electron beam

Gianluca Sarri et al

Located at existing major facilities in Europe, profiting from ongoing investments

- demonstration of major **critical principles**
- construction of **prototypes**
- testing and qualification of prototypes
- construction/testing of **components for construction site(s)**

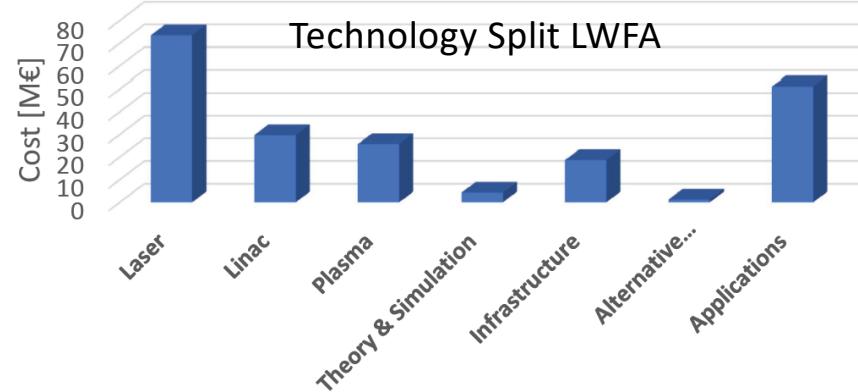
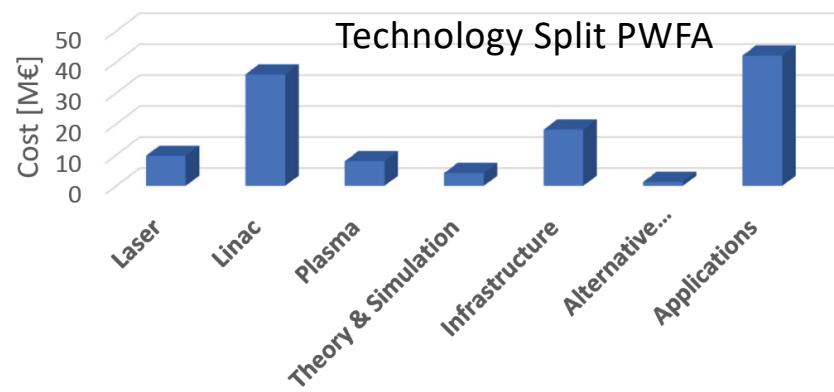




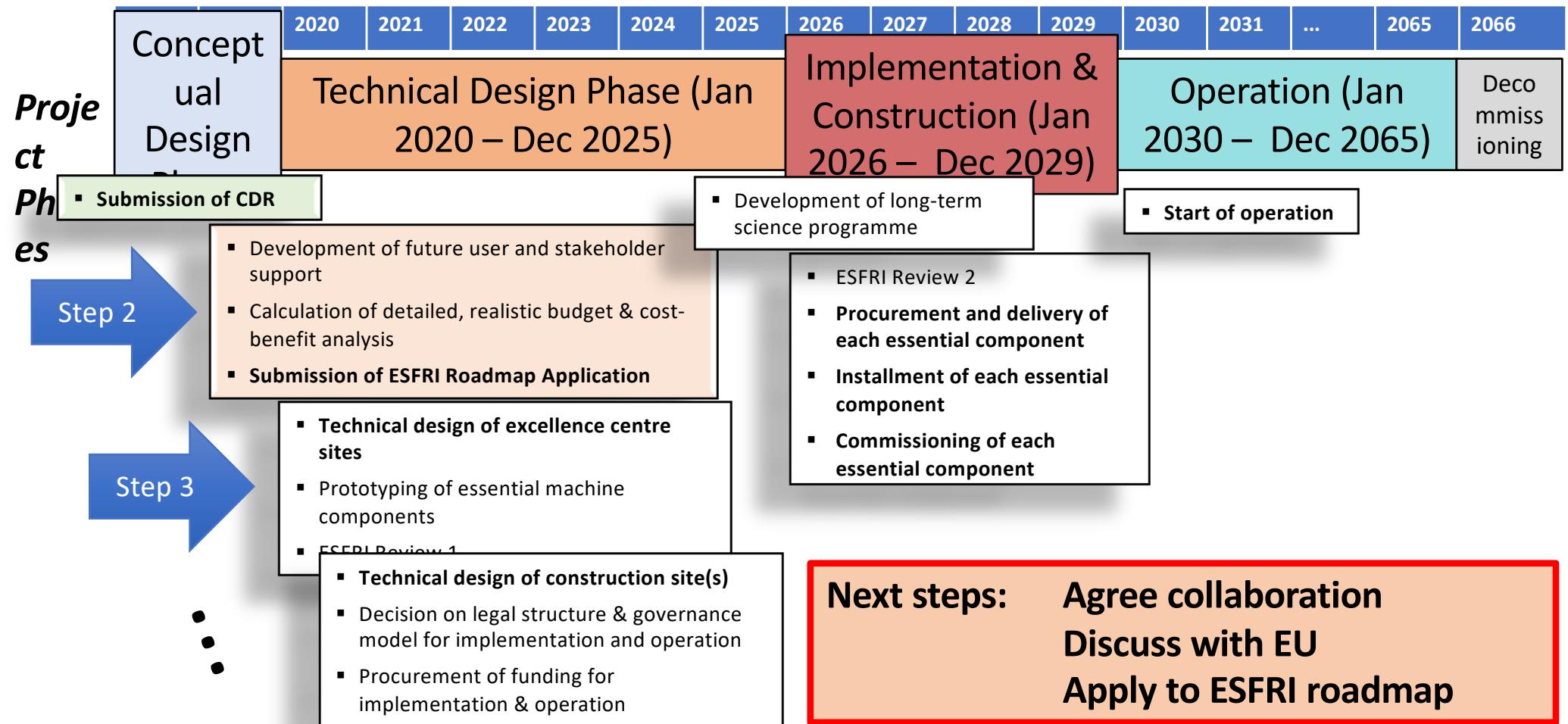
Scenario	Invest
<b>Beam-driven plasma accelerator facility</b>	
Full EuPRAXIA proposal	119 M€
Plasma accelerator facility with FEL	68 M€
<b>Laser-driven plasma accelerator facility</b>	
Full EuPRAXIA proposal	204 M€
Plasma accelerator facility with FEL	110 M€
Minimal laser plasma accelerator with FEL	75 M€

Full cost: 323 M€  
Duration: 8 – 10 years

Reduced cost systems possible, e.g. 1 construction site only, pre-existing invest, ... Full project will be fully European and will bundle capabilities!



# Main Project Milestones & Deliverables



Dans la prochaine décennie, EuPRAXIA a le potentiel de devenir LE centre dédié de R&D accélération laser plasma. (323M€ 2 sites)  
La France (IN2P3, INP, CEA) est bien placé pour:

- Continuer le travail des groupes françaises dans un **TDR (consortium agreement)**
- Devenir un des 5 **excellence center** d'EuPRAXIA .
- Se doter d'une **infrastructure dédiée** pour faire un accélérateur laser-plasma
- **Associer l'industrie** laser française dans le développement des driver
- Développer les **techniques de stabilisation et de fiabilisation** des LPA
- Développer la technologie connexe (**plasmas, aimants permanents,...**)
- Explorer les **applications potentielles** (hors LEL) auprès des installations existantes (e.g. APOLLON) et futures (LAPLACE)

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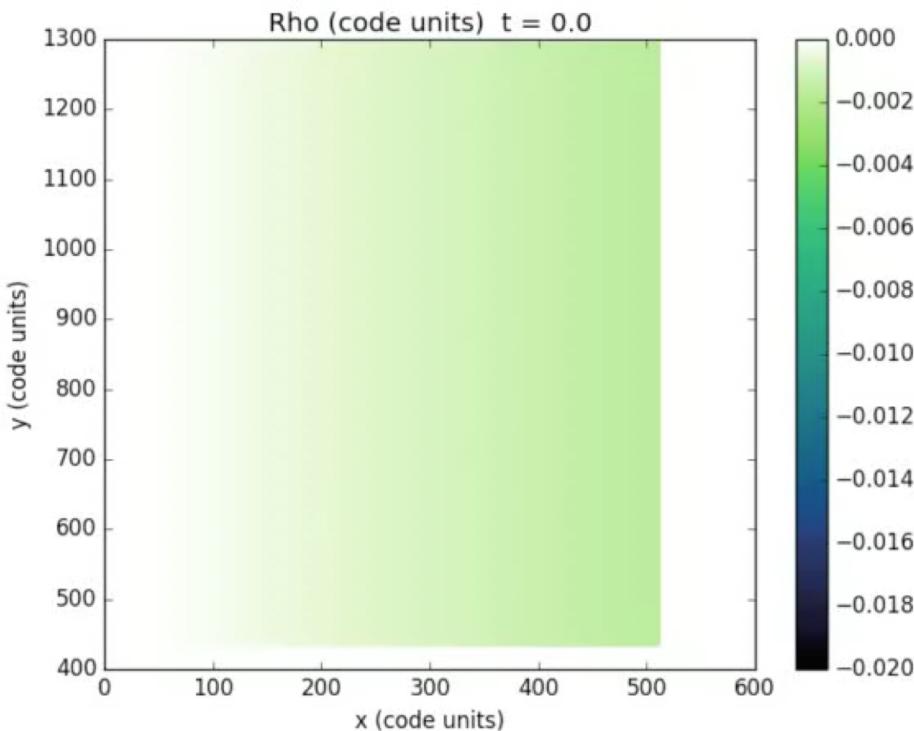
## **extra slides**

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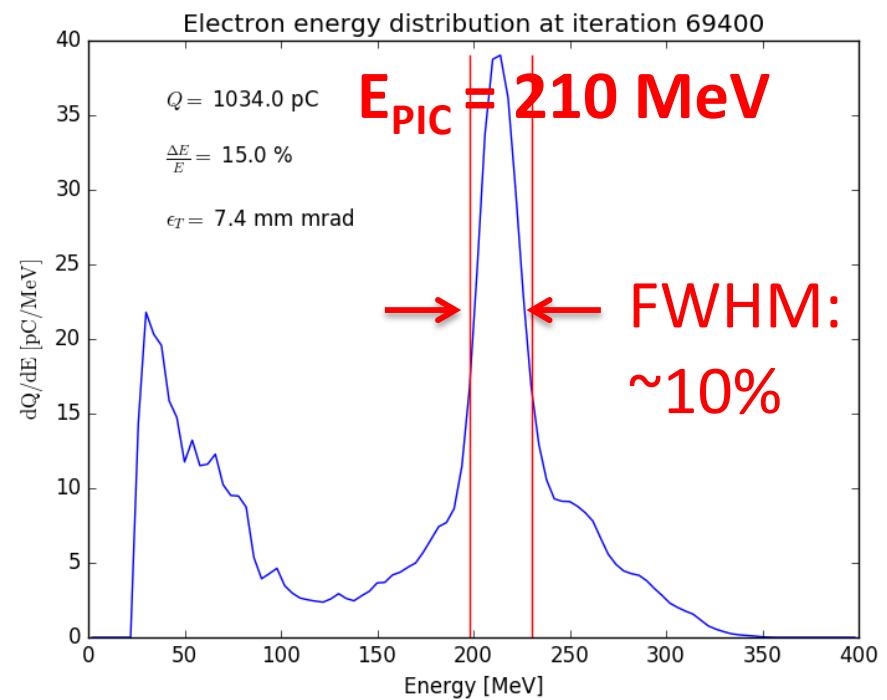
# Physics studies with smilei : APOLLON example

3D PIC Simulation of unguided, unassisted acceleration  
in a ~1 mm thick gas jet -> high yield plasma injector with (1PW)

- plasma  $e^-$  density
- comoving window
- laser moves to the right



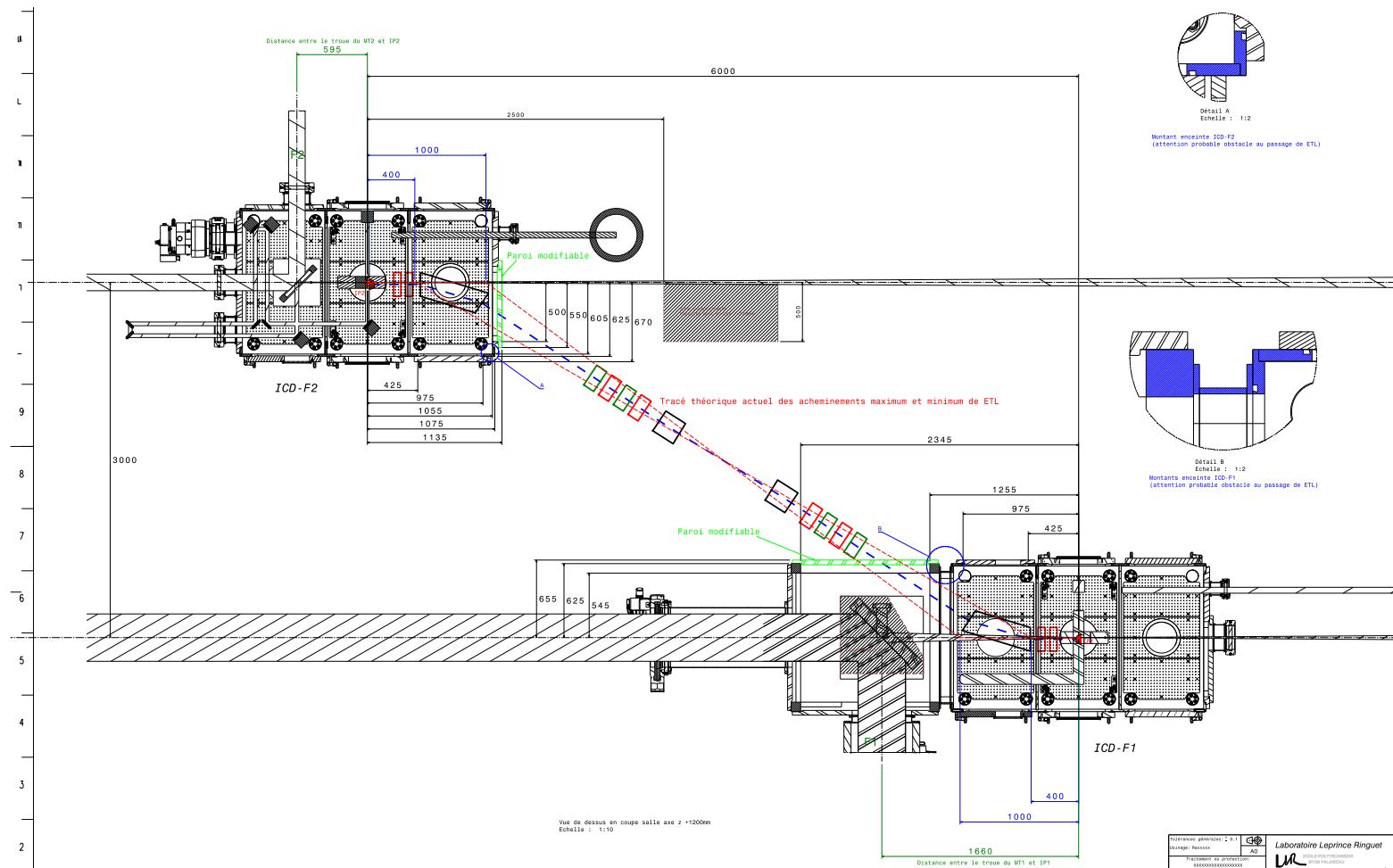
**electron acceleration:**  
**1nC at ~200MeV ex plasma**



- **T1. Exploratory experiments using a single beam**
  - Validate scaling laws & commission the facility (laser parameters, experimental area)
  - Explore new regimes to produce high quality electron beams in the few GeV range
- **T2. Optimize injector (1PW):**
  - >100pC charge electron bunches in the range 50-300MeV, that can be focused at the entrance of the 2<sup>nd</sup> stage.
- **T3. Develop and implement the equipments necessary to**
  - Characterize electron bunches (energy and spatial distribution)
  - Synchronize electron bunch and laser beam
  - Transport electron bunches at the entrance of the second stage
  - Guide the laser beam over large distances (0.1-1 m)

# 2 stage acceleration experiment at CILEX-APOLLON

- Collaboration: LPGP, CEA/IRAMIS, CEA/IRFU, LLR, LULI
  - Laser injector (1PW) + transport-line + laser booster (4PW)



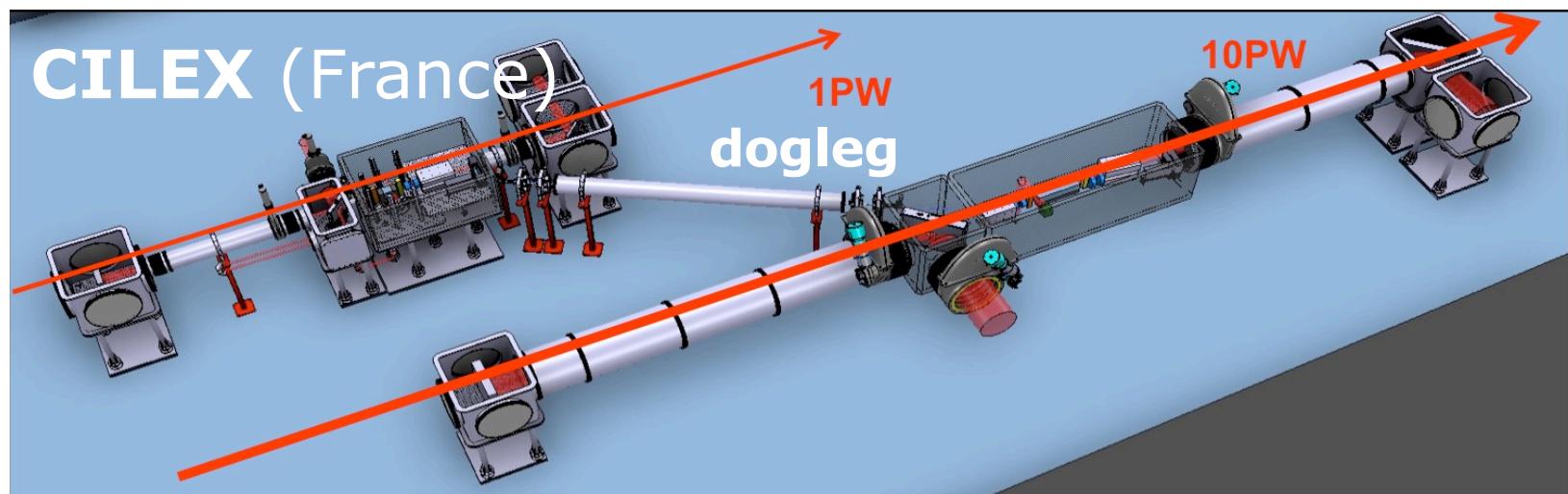


# Enabling multi-stage LWFA - Introduction

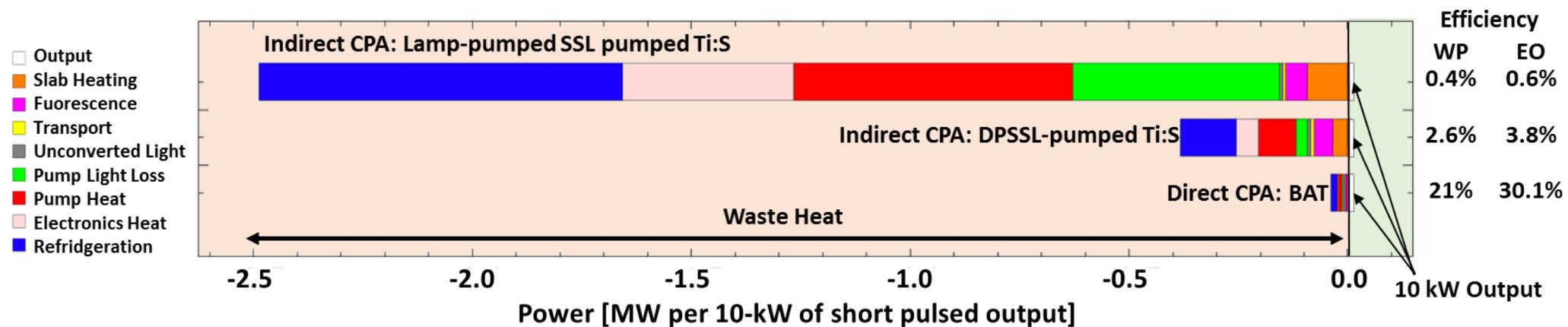


- electron dephasing, laser depletion  
↳ staging of plasma accelerators
- design case = CILEX/APOLLON  
e- acceleration program (>2018)
- plasma injector O(200MeV) and  
plasma booster (5-20GeV)
- coupled by interstage e- transport and  
diagnostics line (dogleg)

$E_{\text{ref}}$	200	MeV
Charge	10	pC
$\epsilon_N$	1	$\mu\text{m}$
$\beta_{x,y}$	1	mm
$\alpha_{x,y}$	0	-
$\sigma_{\Delta E/E}$	1	%
$\sigma_t$	5	fs



Laser efficiency at present is a problem → towards high efficiency solutions, enabling high average power



Courtesy C. Siders, EAAC 2017