

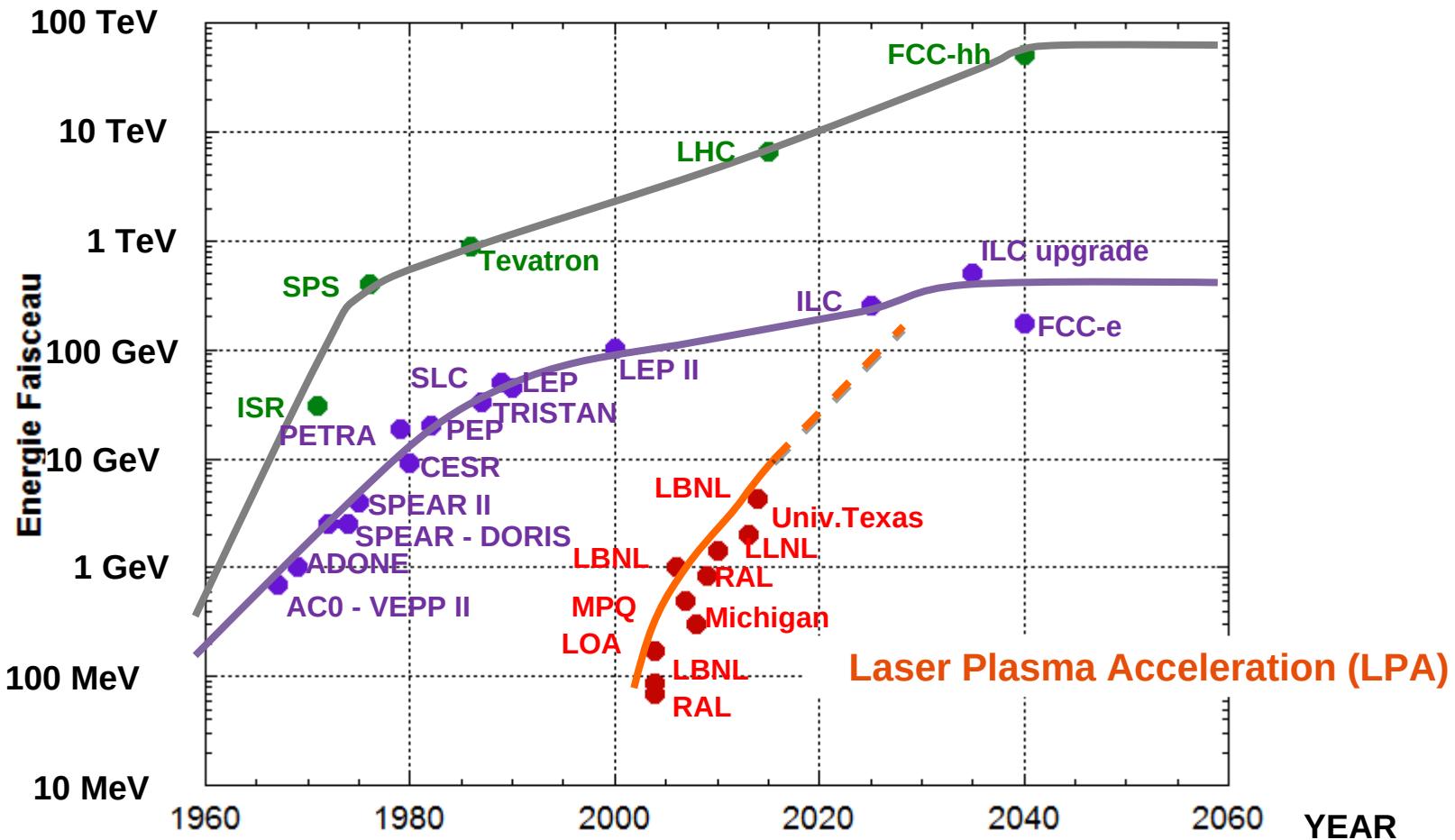


## **Groupe d'Accélération par Laser et Ondes Plasma**

---

Arnaud Beck, Lorenzo Bernardi, Antoine Cauchois, Ali Fahad,  
Ali Mahjoub, Francesco Massimo, Imen Zemzemi, Arnd Speckha

# «beam» energies in laser plasma acc. experiments



LPA gradients 10 to 100 times higher than conventional RF LINACs

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

# Acceleration of e<sup>-</sup> by laser-excited plasma waves at LLR

GOAL: 21st century accelerators should be **smaller, cheaper and more powerful!**  
→ increase acceleration gradient (MeV/m) 10-100 times (w.r.t. conventional RF)

LLR 2019: 7 FTE (Scientists+Engineers), 2 permanents (CNRS)



High-performance high-fidelity  
plasma simulation



CILEX/APOLLON : electron acceleration experiments with peta-watt lasers



Prepare the future of accelerators

- Ø [EuPRAXIA \(H2020, future infrastructures\)](#)
- Ø [ARIES \(H2020 Integrating activity\)](#)



# Collaborations

---

- Collaborations locales:
  - IPP: LULI, LOA (ENSTA)
  - UPSay: LPGP, IJC Lab (ex-LAL Orsay )
  - CEA et autres: IRFU, IRAMIS, Maison de la Simulation, Synchrotron SOLEIL
  - GDR APPEL Accelerateurs laser plasma
- Collaborations européennes et internationales:
  - DESY, CERN
  - U OXFORD
  - U Berkeley
- Infrastructures (existantes et futures)
  - LOA Salle jaune, CEA UHI100
  - APOLLON, Supercalculateurs: CINES, TGCC, IDRIS
  - LAPLACE?, PALLAS (Orsay)?, EuPRAXIA



Open-source  
PIC code

**Collaborative, user-friendly**  
GitHub • python interface

**Educational resources**  
online documentation • tutorials

**High-performance**  
MPI-OpenMP • load balancing • vectorization

**Physics**  
ionisation • collisions • strong-field QED

**Advanced solvers**  
high orders • multi-geometries • laser envelope

M. Grech  
F. Perez  
T. Vinci

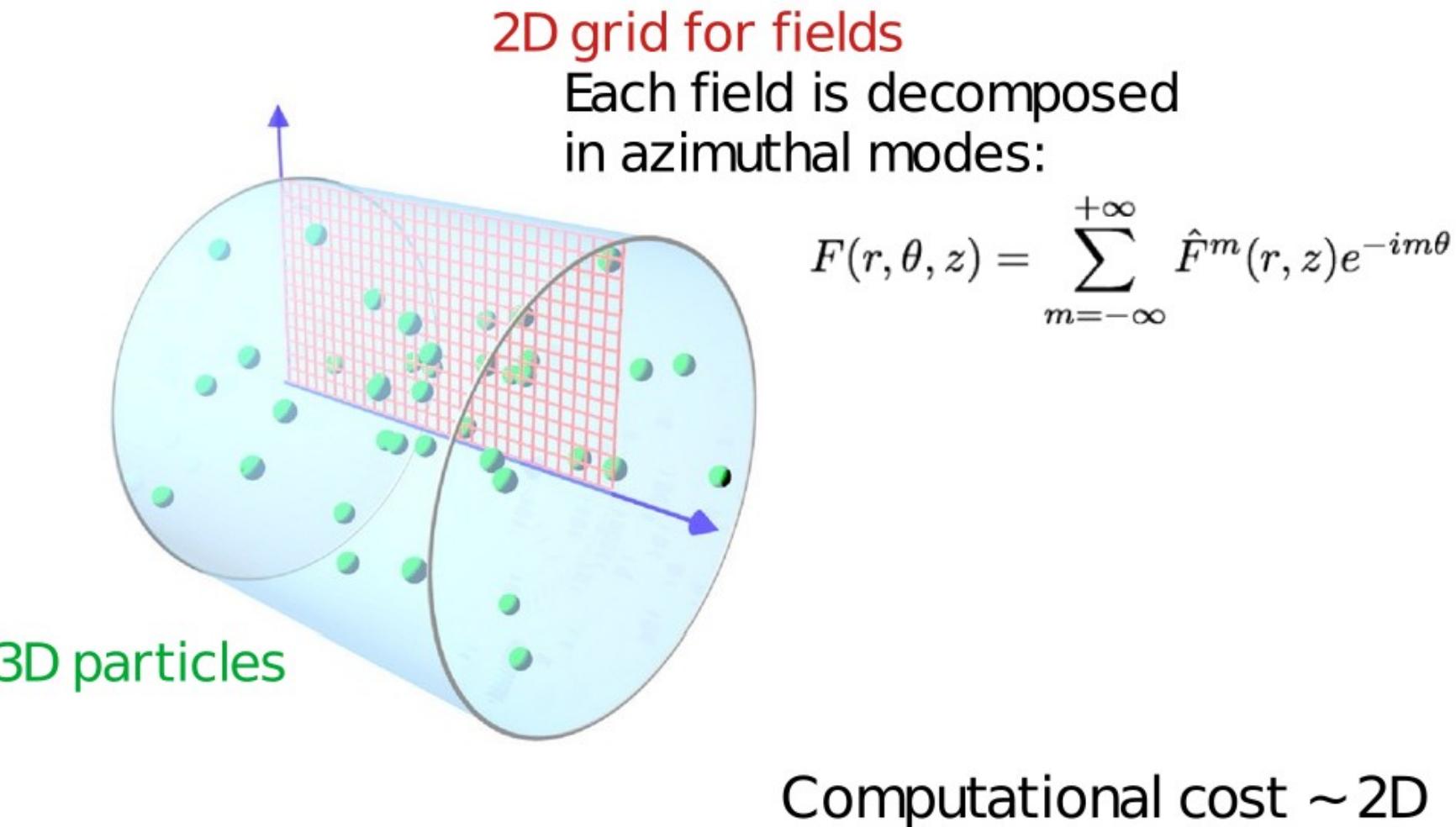
J. Dérouillat  
M. Lobet



A. Beck  
F. Massimo  
I. Zemzemi  
...and many more

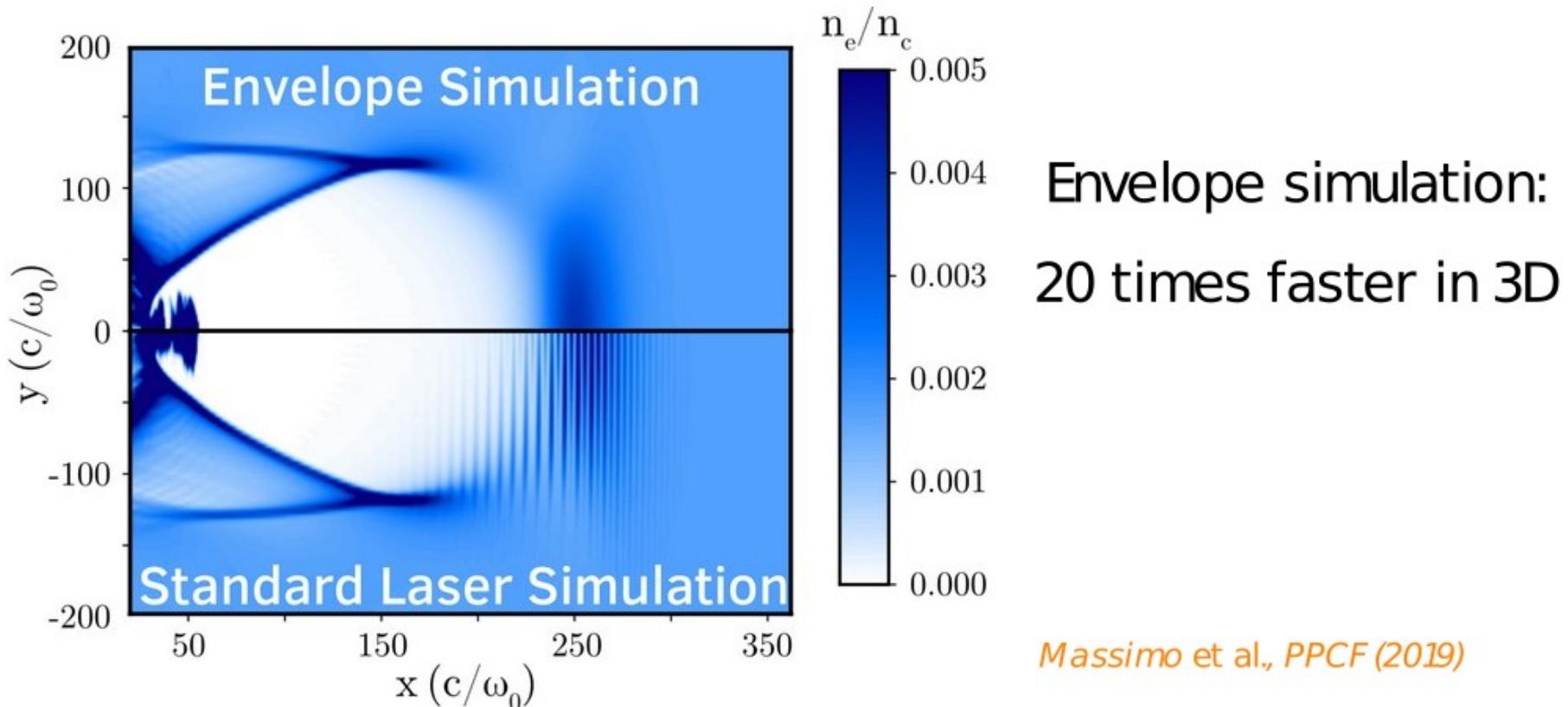


# Azimuthal-modes geometry: fast & reliable



# Envelope approximation for faster simulations

- Full-PIC = resolve the laser wavelength
- Approximation : reduced equations on laser envelope

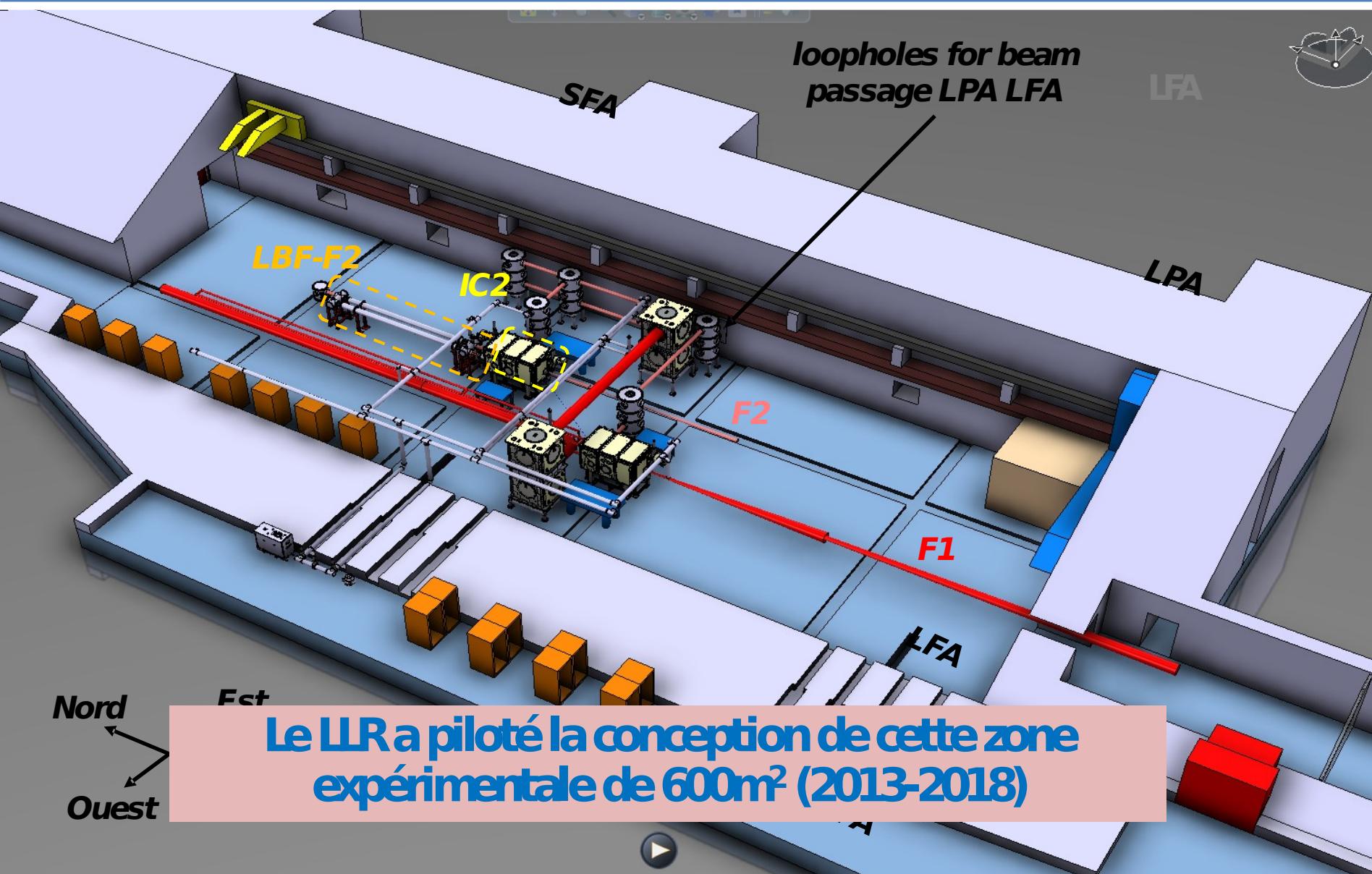


---

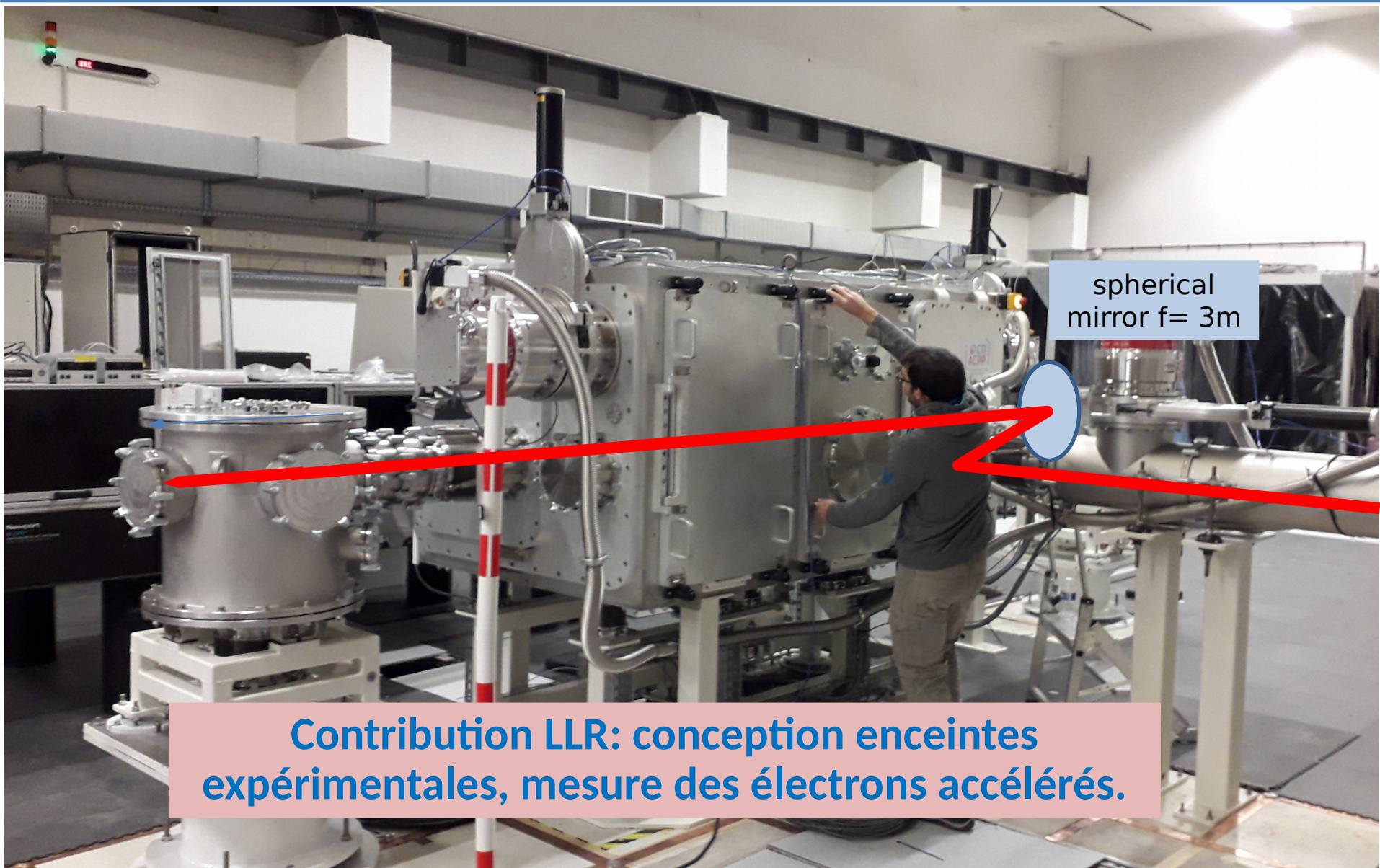
# LASER APOLLON

**Expériences d'accélération par sillage laser plasma**

# Long Focal Area (electron acceleration)

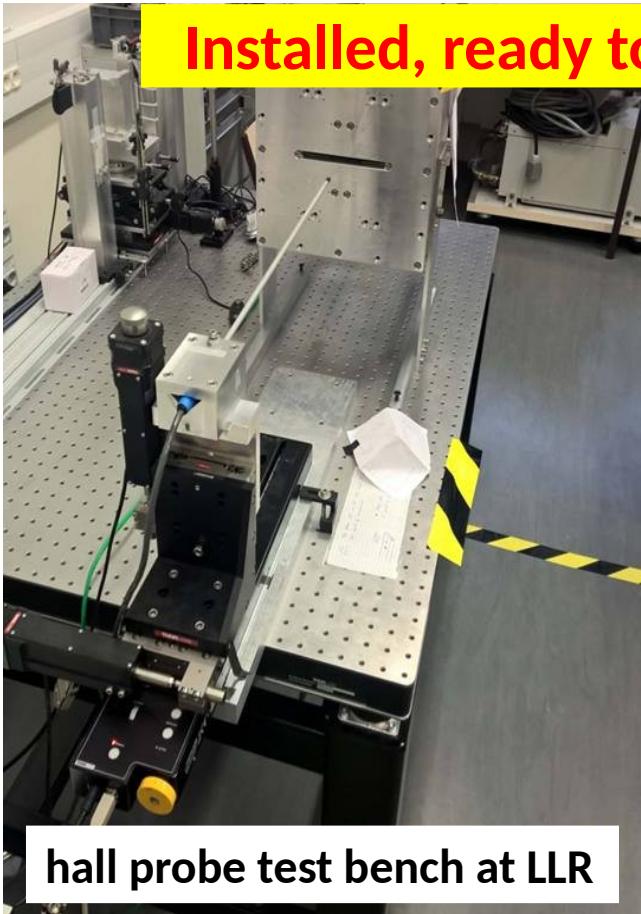


# Preparation of 1<sup>st</sup> e<sup>-</sup> acceleration experiment at APOLLON 1PW

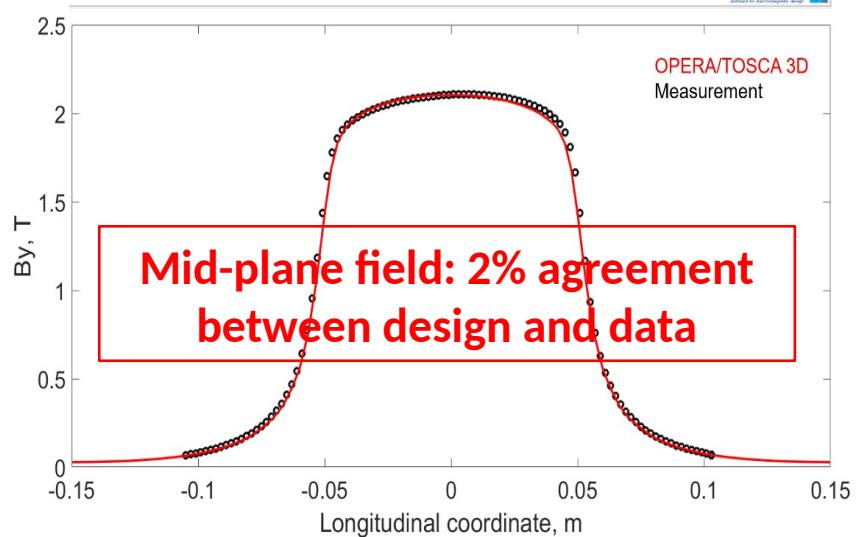
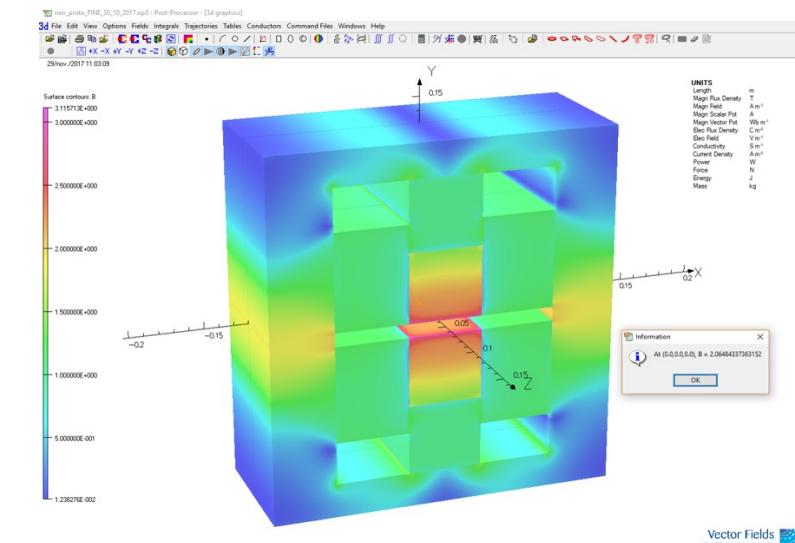


# Tech. development: 2.1 Tesla permanent dipole magnet (2017)

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

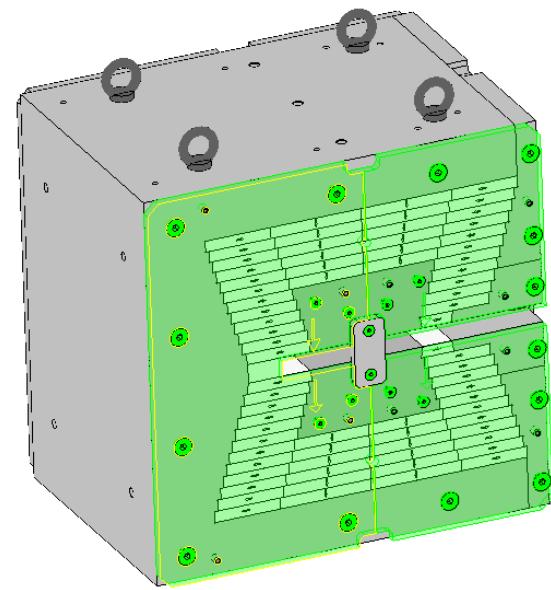
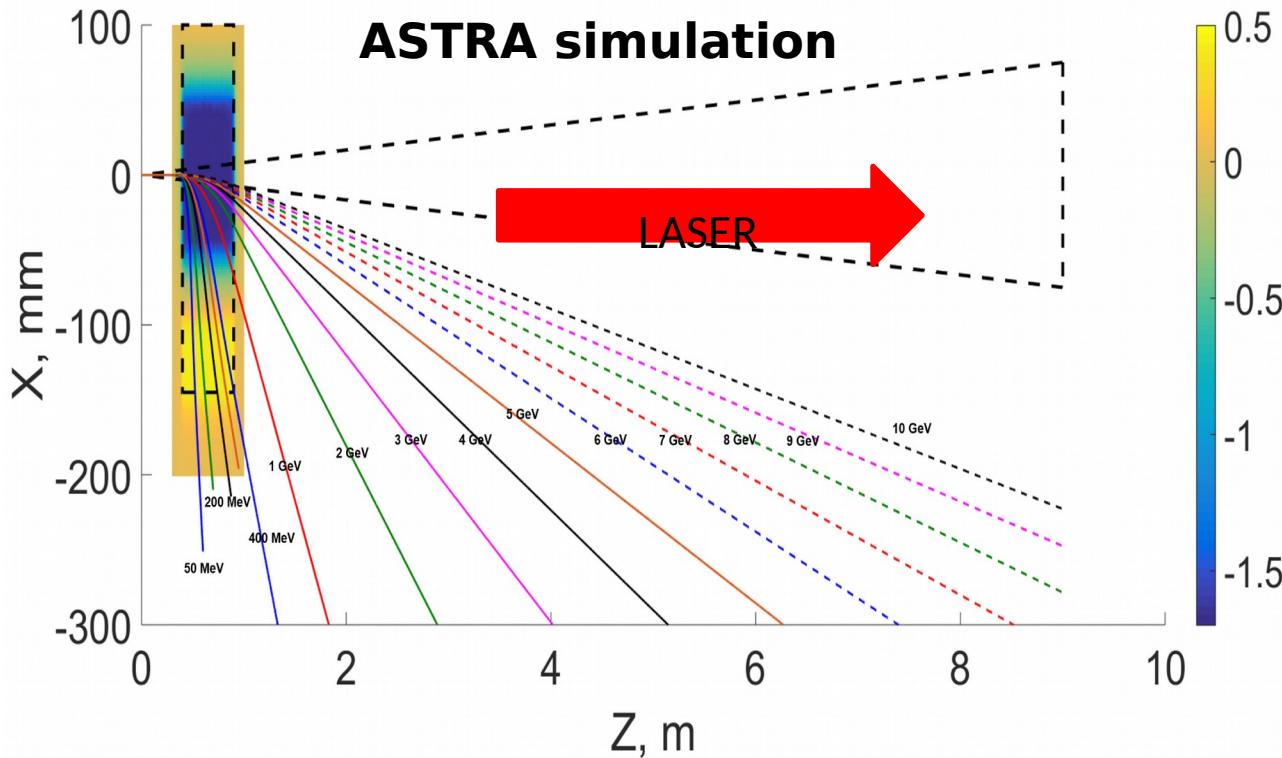


M.Kojoyan et al., ICAP 2018 Proceedings, JACoW  
M.Kojoyan et al., IBIC 2018 Proceedings, JACoW



# Tech development: 1.7 Tesla permanent dipole magnet (2019)

- spectrometer for **APOLLON 5-10 PW**
- energy range: 200 MeV – 12 GeV



designed by LLR,  
manufactured by industry,

delivery: july 2019  
**READY!**

# Expériences CILEX-APOLLON

---

ATOUTS LLR: compétences en technologies « particules » appliquées à la physique expérimentale utilisant des lasers

- 2020 (si autorisation de tir ASN)  
1ere exp., régime non-linéaire, laser 1PW -> électrons=0,2–1 GeV
- Développement Instrumentation pour APOLLON
  - aimants focalisant innovants  
(= quadripôles permanents, exposés en salle)
  - détecteurs dans le vide
- Perfectionnement du spectromètre à électrons:  
=> caractérisation complète des électrons (émittance et spectre)
- Conception d'une éjection du faisceau: applications

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



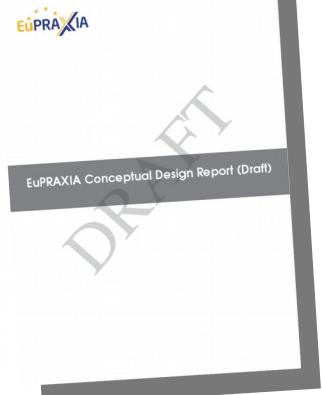
**The EuPRAXIA team**

P. D. Alesini, A. S. Alexandrova, M. P. Anania, N. E. Andreev, R. W. Assmann, T. Audet, A. Bacci, I. F. Barna, A. Beaton, A. Beck, A. Beluze, A. Bernhard, S. Bielawski, F. G. Bisesto, J. Boedewadt, F. Brandi, O. Bringer, R. Brinkmann, E. Bründermann, M. Büscher, G. C. Bussolino, A. Chance, M. Chen, E. Chiadroni, A. Cianchi, J. Clarke, M. Croia, M. E. Couprise, B. Cros, J. Dale, G. Dattoli, N. Delerue, O. Delferriere, P. Delinikolas, J. Dias, U. Dorda, K. Ertel, Á. Ferran Pousa, M. Ferrario, F. Filippi, J. Fils, R. Fiorito, R. A. Fonseca, M. Galimberti, A. Gallo, D. Garzella, P. Gastinel, D. Giove, A. Giribono, L. A. Gizzi, F. J. Grüner, A. F. Habib, L. C. Haefner, T. Heinemann, B. Hidding, B. J. Holzer, S. M. Hooker, T. Hosokai, B. Imre, D. A. Jaroszynski, C. Joshi, M. Kaluza, O. S. Karger, S. Karsch, E. Khazanov, D. Khikhlikha, A. Knetsch, D. Kocon, P. Koester, O. Kononenko, G. Korn, I. Kostyukov, L. Labate, C. Lechner, W. P. Leemans, A. Lehrach, F. Y. Li, X. Li, A. Lifschitz, V. Litvinenko, W. Lu, A. R. Maier, V. Malka, G. G. Manahan, S. P. D. Mangles, B. Marchetti, A. Marocchino, A. Martinez de la Ossa, J. L. Martins, K. Masaki, F. Massimo, F. Mathieu, G. Maynard, T. J. Mehrling, A. Y. Molodozhentsev, A. Mosnier, A. Mostacci, A. S. Müller, Z. Najmudin, P. A. P. Nghiem, F. Nguyen, P. Niknejadi, J. Osterhoff, D. Papadopoulos, B. Patrizi, R. Pattathil, V. Petrillo, M. A. Pocsai, K. Poder, R. Pompili, L. Pribyl, D. Pugacheva, S. Romeo, A. R. Rossi, A. A. Sahai, Y. Sano, P. Scherkl, U. Schramm, C. B. Schroeder, J. Schwindling, J. Scifo, L. Serafini, Z. M. Sheng, L. O. Silva, C. Simon, U. Sinha, A. Specka, M. J. V. Streeter, E. N. Svystun, D. Symes, C. Szwarz, G. Tauscher, A. G. R. Thomas, N. Thompson, G. Tocci, P. Tomassini, C. Vaccarezza, M. Vannini, J. M. Vieira, F. Villa, C. G. Wahlström, B. Walczak, P. A.

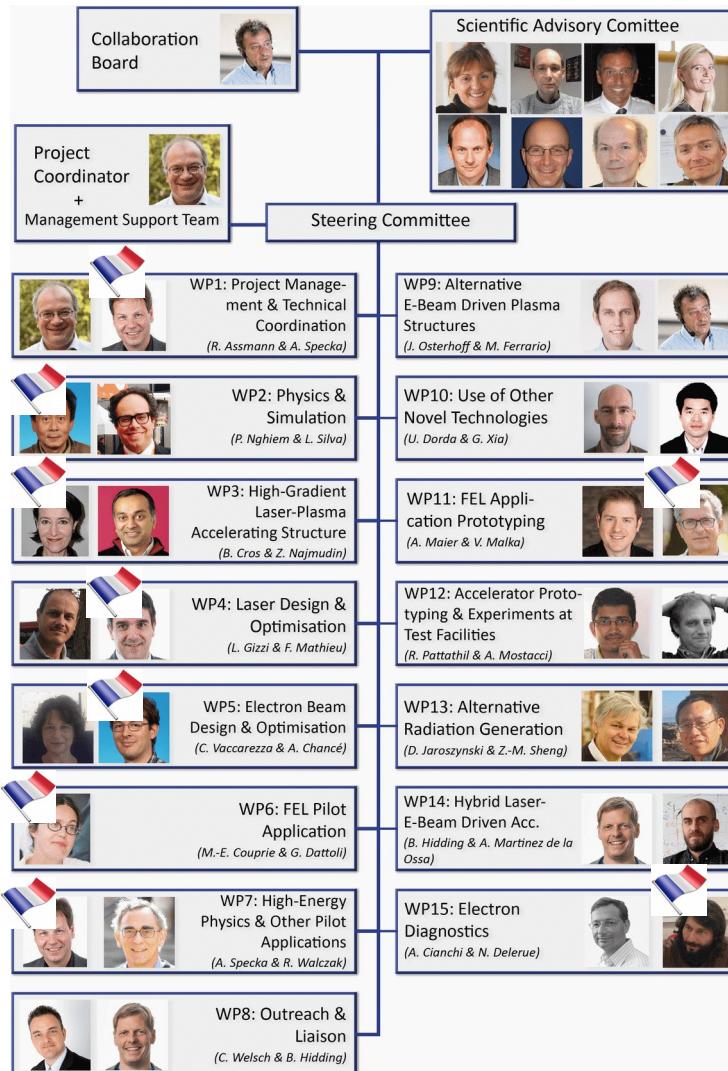
# The EuPRAXIA Project

**EU funded Consortium (3 M€) to produce a CDR for a European Research 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



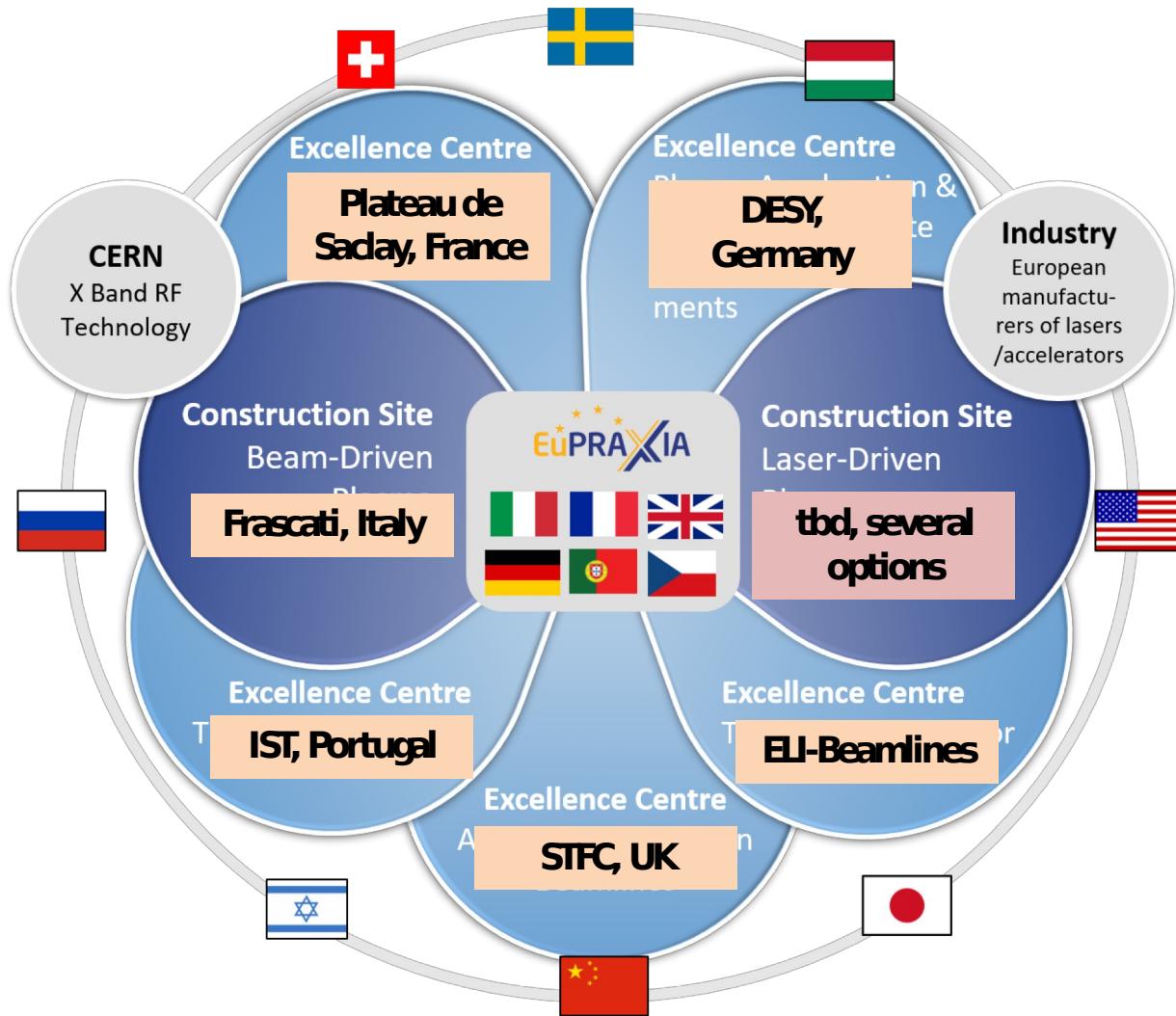
**Main deliverable:  
CDR published in 2019  
555 pages**



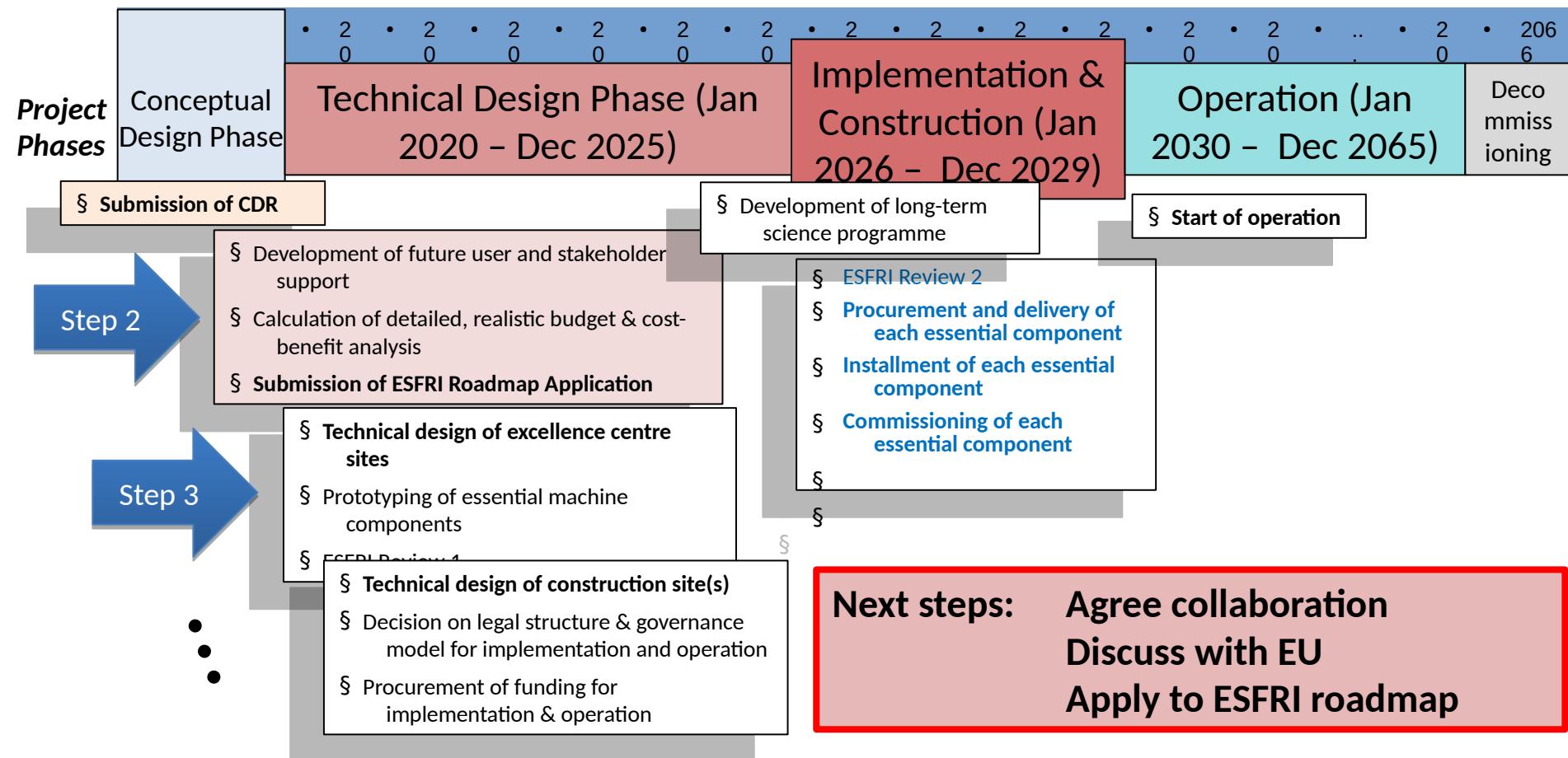
# EuPRAXIA Model and Sites

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)**



# Main Project Milestones & Deliverables



# Projet Européen EUPRAXIA

---

- ATOUTS:
  - implication forte des équipes locales (plateau et vallée) dans la design study
  - concentration de compétences en technologies laser, accélérateur, détection, simulation
- Promouvoir le projet EuPRAXIA dédié à l'accélération laser d'électrons (ciblage thématique) : ⇒ participer au *technical design report*
- Fort soutien de l'IN2P3 et l'INP: GDR APPEL (crée en 2019)
- Créer un centre d'excellence EuPRAXIA en France:
  - PALLAS (IJCLab) → fiabilisation, multi-étage
  - LAPLACE (ENSTA) → haute cadence, prototype laser électrons libre
  - APOLLON → très hautes énergies, applications de faisceaux secondaires
  - SMILEI → simulations, formation, diffusion

---

## ANNEX 3

### **Complementary information**

# Responsabilities of GALOP members (2014-18)

## France

- Specka
  - CILEX APOLLO N
    - 2013– 2019
      - **scientific coordinator of long focal exp. area**
      - member of the steering committee
    - GDR APPEL
      - 2018–
        - coordinator axis “Simulation” (**Beck**)
        - coordinator axis “Experimental activities” (**Specka**)

Specka • IN2P3

- 2016– responsible for master-project IN2P3 ALP-electrons



Beck SMILEI

- 2015– co-founder and core developer

Specka Polytechnique

- 2016– 2019
  - bachelor program: academic advisor for phys



## • International

- Speckia
  - EuPRAXIA (H2020,3M)
    - **deputy project coordinator**
    - –2019
      - Acceleration Laser Plasma Accelerator (ALPA)
      - **workpackage coordinator (HEP applications)**



# Strength-Weaknesses-Opportunities-Threats (SWOT)

---

- **Strengths:**

- Expertise in electron beam diagnostics in LPA experiments
- Expertise in operation and development of plasmas simulations
- New competence in permanent magnet design and prototyping
- Capability to bridge the scientific culture in pluridisciplinar program

- **Opportunities:**

- Declared will of CILEX-APOLLON to favorize a durable R&D program on electron acceleration
- High visibility and integration in EU networks and projects (EuroNNAC, EuPRAXIA, ARIES)
- Strong support by IN2P3 for this novel accelerator technology

# Strength-Weaknesses-Opportunities-Threats (SWOT) cont'd

---

- **Weaknesses:**

- small number of permanent researchers
  - over-commitment of responsibilities on one single person
  - worst case in 2019: 40% decrease of staff
- decreasing technical support at LLR

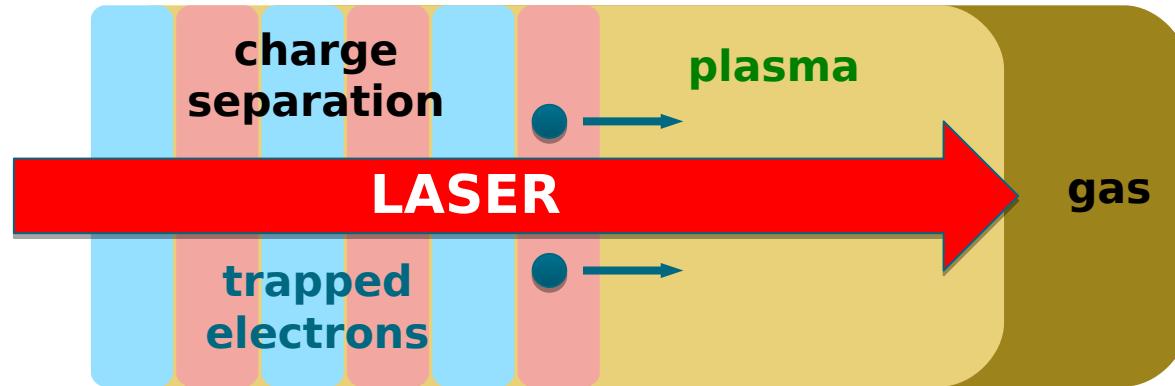
- **Threats:**

- Dependence on GENCI for computation time allocation
- Small repetition rate of APOLLON laser (1/min) will limit fiabilisation studies
- Insufficient technical ressources allocated by CILEX-APOLLON
- Operation of APOLLON as user facility can compromise a collaborative long-term program
- Disappearance of internationally recognized brand name CILEX

# Physics principle of laser plasma wave acceleration

T. Tajima and J. M. Dawson Phys. Rev. Lett. 43, 267 (1979)

- ultra-short pulse, high peak-power laser : >50TW, 20-100fs, >1 J, focused in a gas, e.g. hydrogen

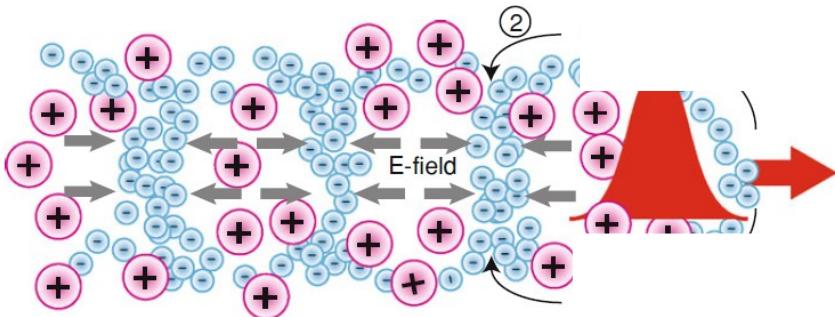


- laser wakefield acceleration of electrons (LWFA)
  - gaseous target (under-dense plasma) :  $n_e \sim 10^{16} - 10^{19} \text{ cm}^{-3}$
  - field effect ionization at the front of the laser pulse
  - charge separation -> plasma wave:  $\lambda_p \sim 300\mu\text{m} - 10\mu\text{m}$
  - phase velocity  $v_{ph}$  (plasma wave) =  $v_g$  (group velocity laser) => relativistic wave

# Plasma wave driven by strong electric fields

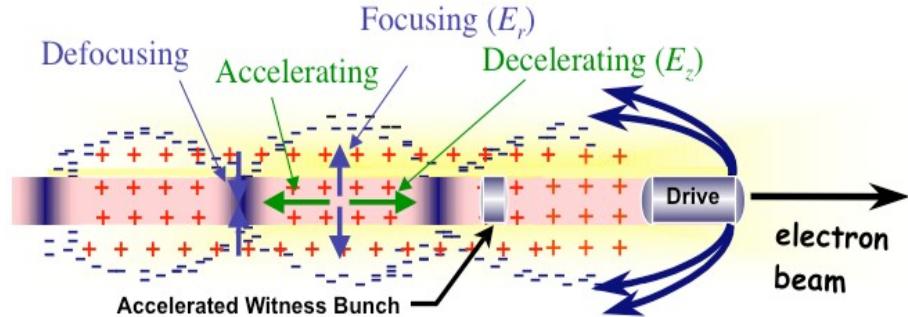
## laser field (vector potential $a$ )

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

plasma wave

ponderomotive  
force

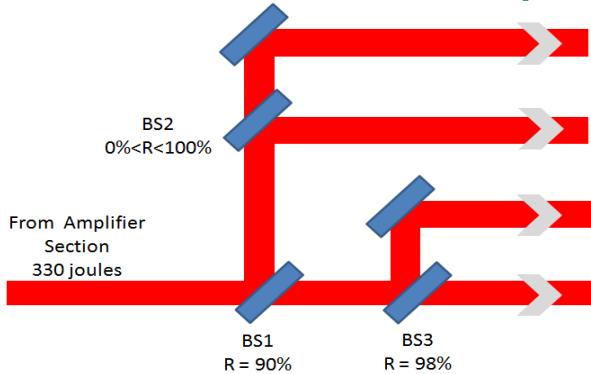
1-D linear approximation

space  
charge force

# Centre Interdisciplinaire de Lumière Extreme (CILEX)

- CILEX = LASER APOLLON (15M€)  
+ 2 salles expérimentales équipées (15M€)

- 4 faisceaux indépendants, énergies variable



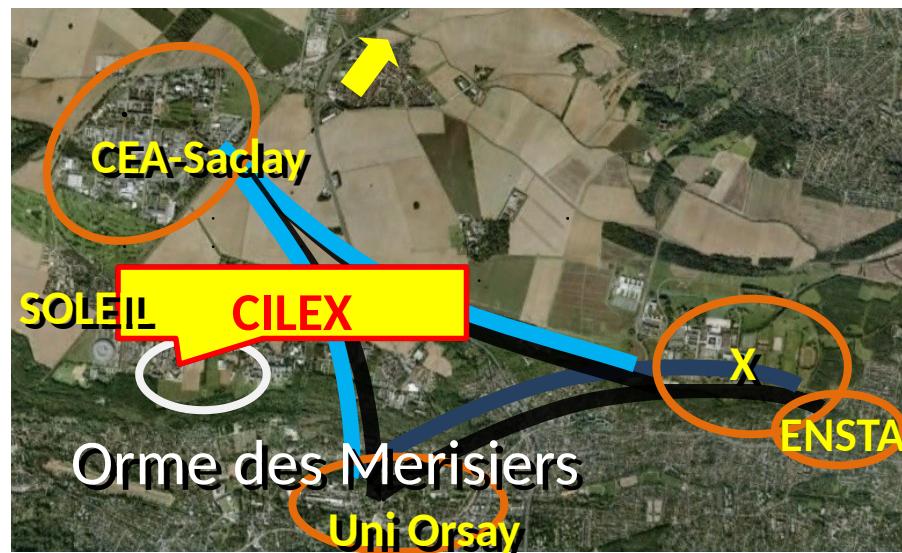
**10PW: 15fs -1 ps / 150J**

**1PW: 15fs - 1 ps / 15J,**

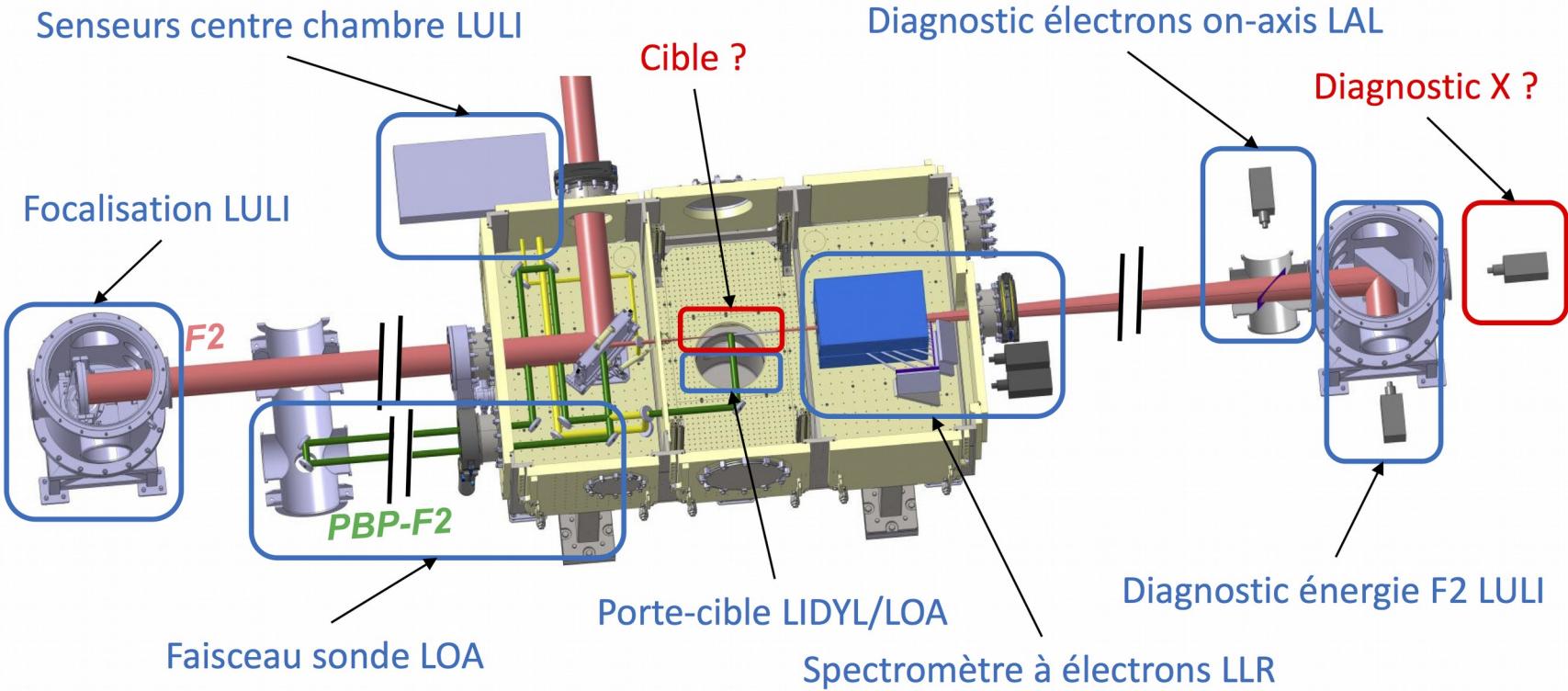
uses CPA (Chirped Pulse Amplification), Nobel Prize 2018

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

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



# First experiments on CILEX-APOLLON 1PW Laser (Jan 2019)



2019: « qualification experiments »: demonstrate laser capabilities

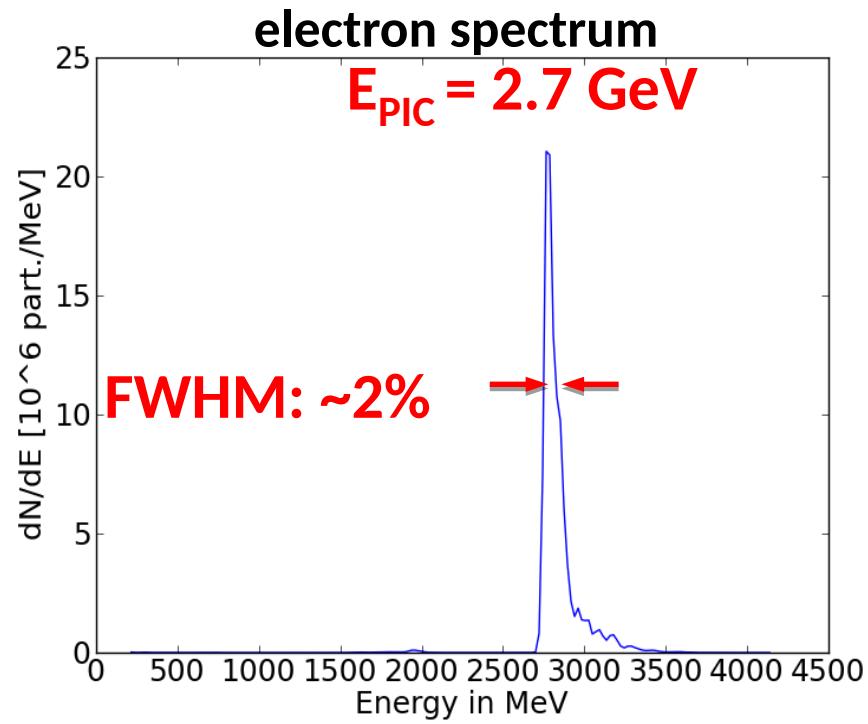
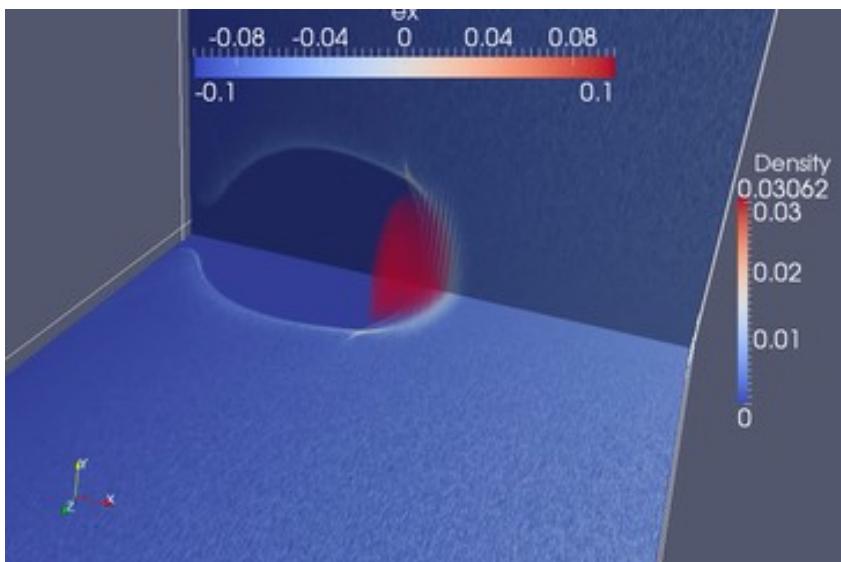
2020: Target 1 of CILEX scientific program: bubble regime w/ 1 beam

# CILEX-APOLLON: simulation of first experiments

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

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

ion bubble shrinks, then expands



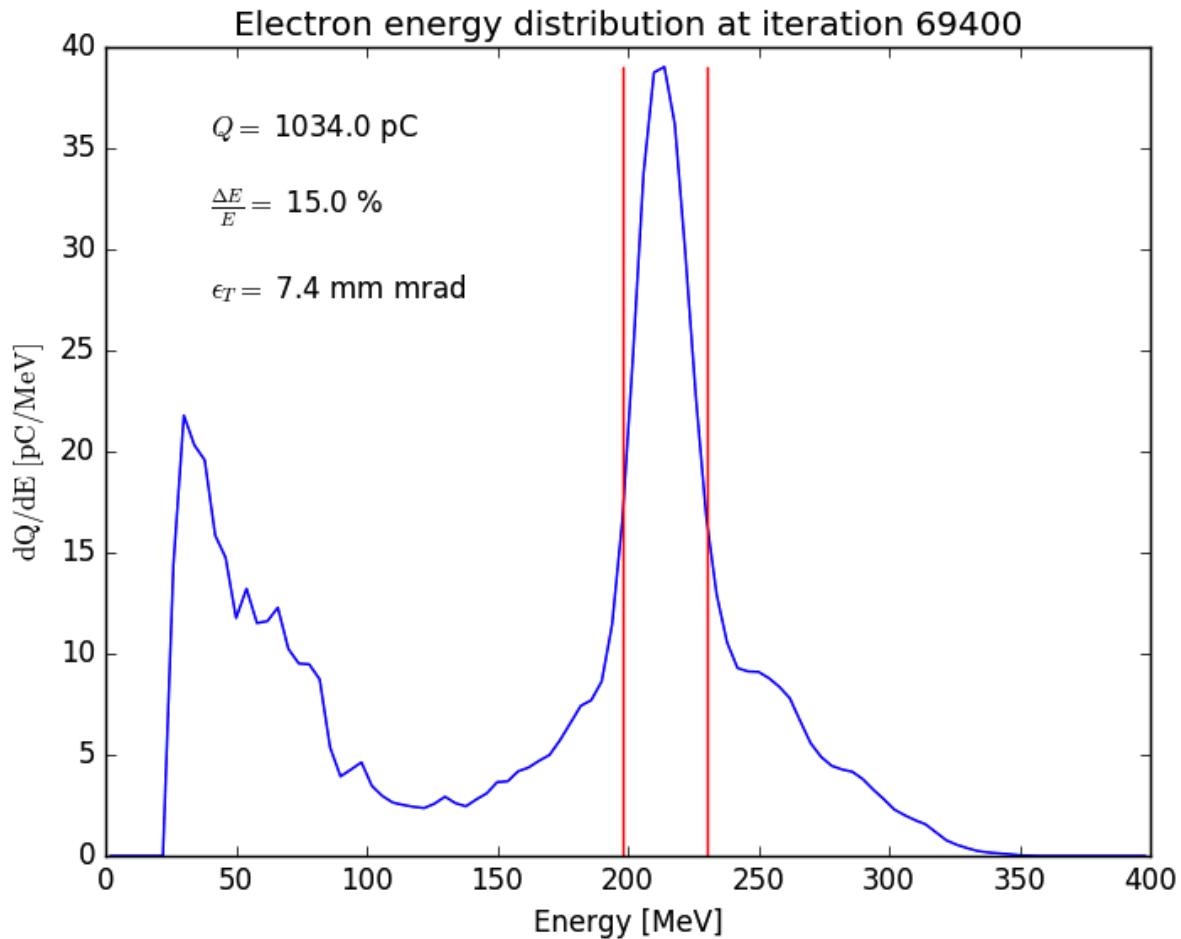
- stable acceleration over « long distances without laser guiding
- energy spectrum peaks around ~3 GeV after ~20mm propagation

# Physics studies: example

- 3D PIC Simulation (SMILEI code) of unguided, unassisted acceleration in O(1mm) gas jet -> high yield injector w/ F2 (1PW)

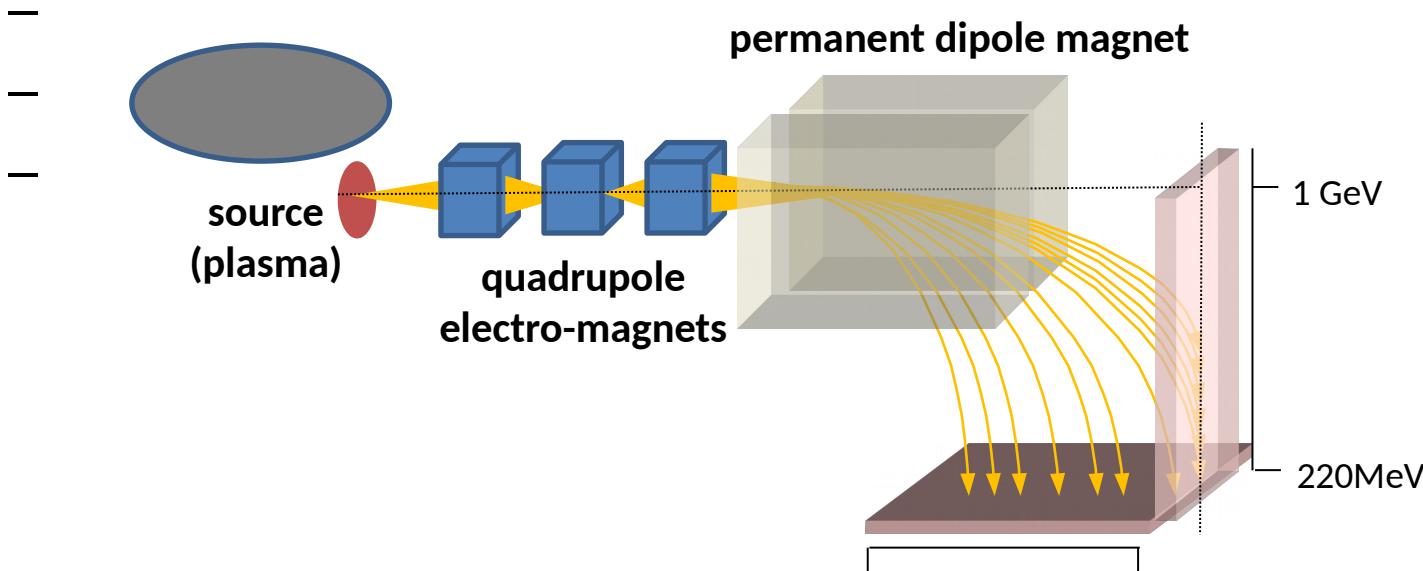


- $\lambda_0 = 0.8 \mu\text{m}$
- $a_0 = 2.56$
- $\tau_L = 20 \text{ fs}$
- $w_0 = 40 \mu\text{m}$
- $E = 7.5 \text{ J}$
- $P = 350 \text{ TW}$
- $n_0 = 5.0 \times 10^{18} \text{ cm}^{-3}$
- $L_{\text{ramp}} = 0.1 \text{ mm}$
- $L_{\text{tot}} = 1.65 \text{ mm}$



# CILEX-APOLLON experiments: Future plans

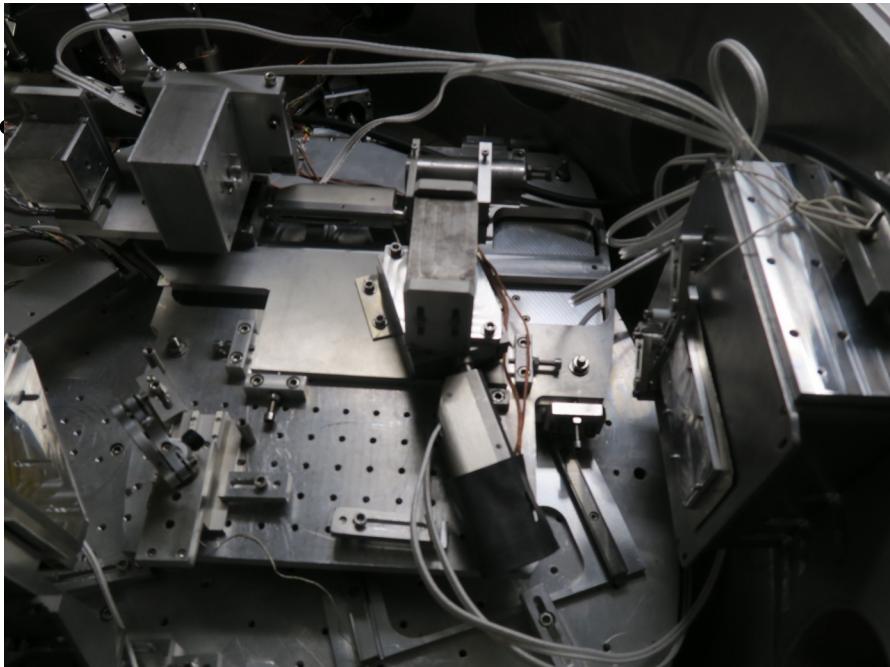
- 2019: commissioning of APOLLON 1PW laser
  - complete and commission electron detection (screens)
  - study of bubble regime with 1PW laser  $\rightarrow E \sim 3 \text{ GeV}$
  - full 1PW performance  $\Rightarrow 9\text{m focal length (longer acceleration length)}$   
 $\Rightarrow$  demonstrate multi-GeV capability of
  - complete spectrometer: quadrupole focussing  
 $\Rightarrow$  emittance measurement, beam ejection for applications



# Collaboration DACTOMUS (IRFU, IRAMIS, LAL, LPGP, LLR)

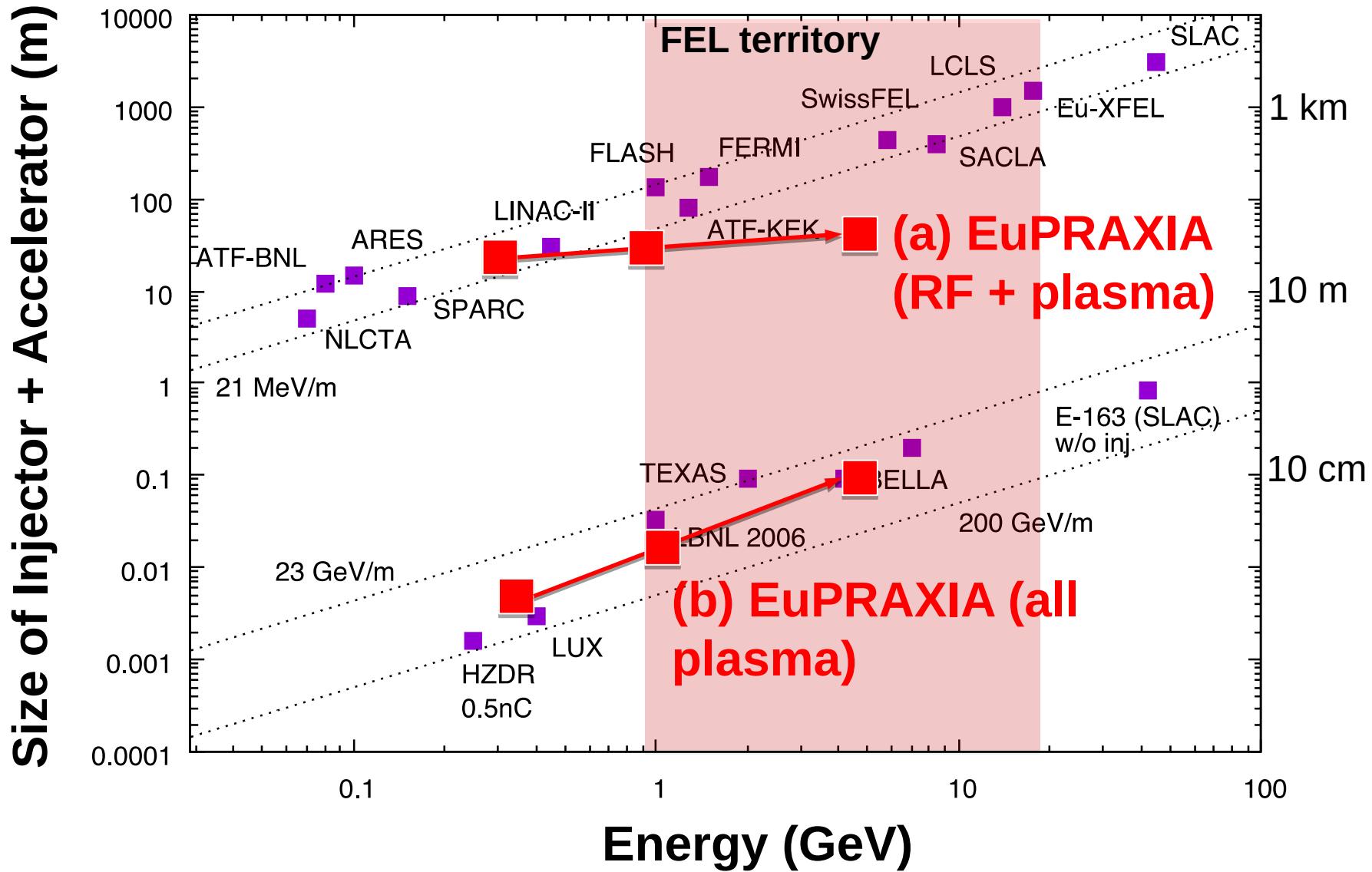
- Expériences LWFA 1 étage sur le laser 100TW UHI100 (Saclay) (jan 2017)
- objectif: transport compact des électrons
- test de quadripôles compacts ( $L=50\text{mm}$   $\varnothing 6\text{mm}/300\text{Tm}^{-1}$  &  $\varnothing 12\text{mm}/140\text{Tm}^{-1}$ )
- spectromètre compact 100-200MeV
- 

## Zoom magnétique

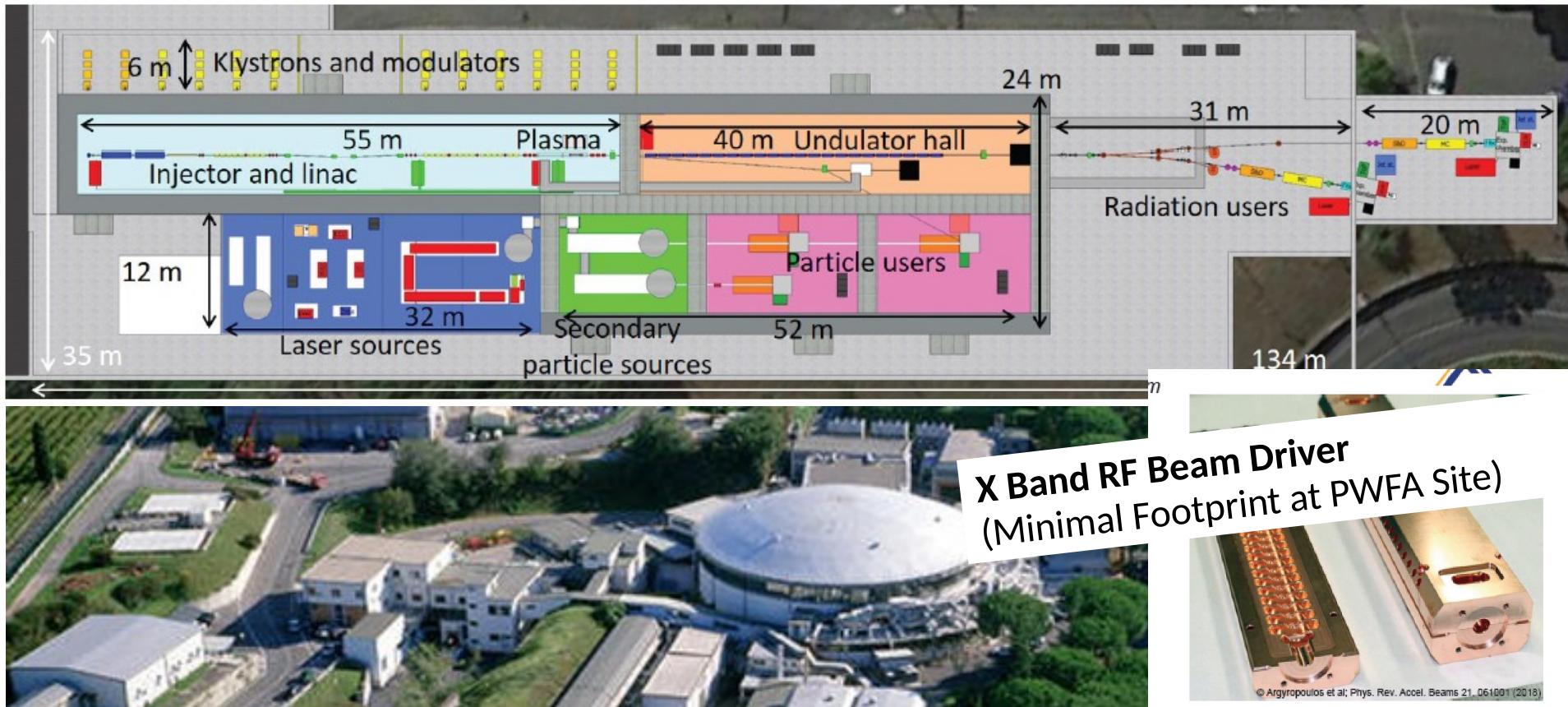


Accélération Laser Plasma (Visite DER au LLR)

towards high quality electron beams



# Beam-Driven EuPRAXIA Site at INFN Frascati



# Cost Estimate in CDR (to be detailed and reviewed in technical design phase)

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!

