Electron acceleration at CILEX-APOLLON

Centre Interdisciplinaire de Lumiere EXtreme

Interdisciplinary Center for Extreme Light

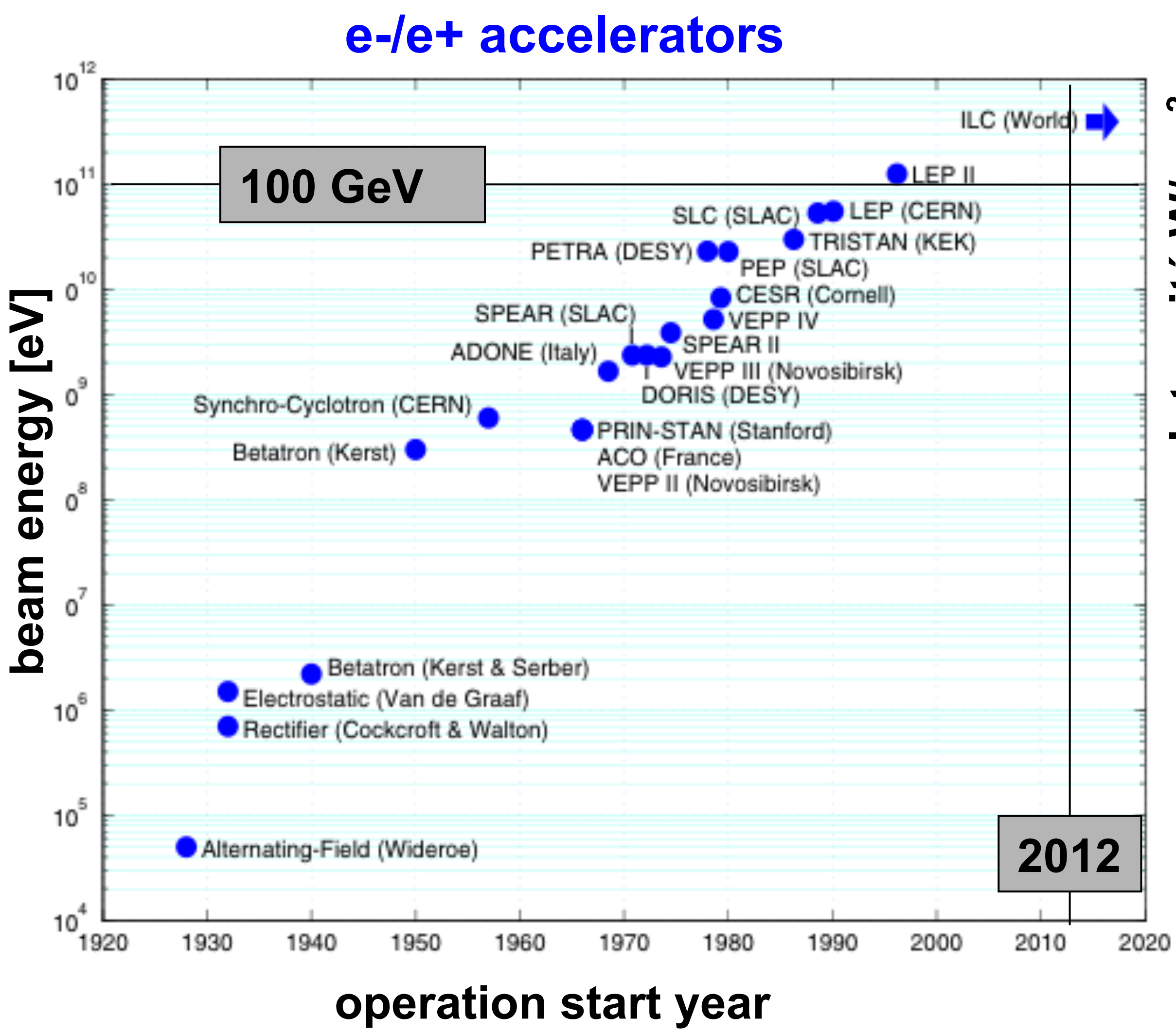
Arnd Specka, Laboratoire Leprince–Ringuet, Ecole Polytechnique – CNRS/IN2P3, Palaiseau, France

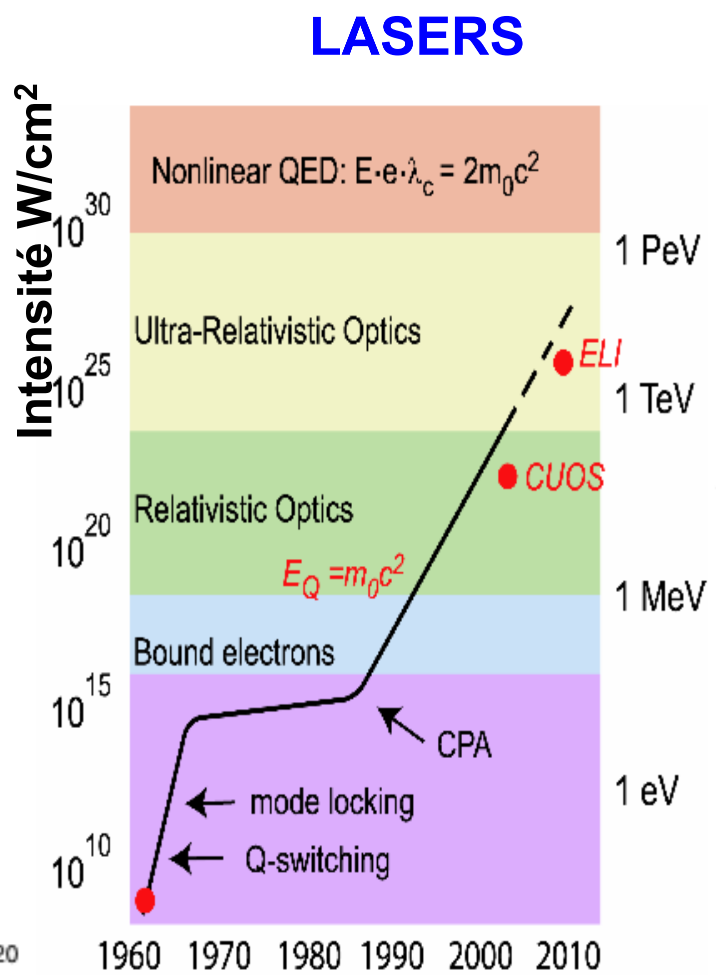
on behalf of the CILEX collaboration

many thanks to:

F. Amiranoff, P. Audebert, J.F. Bethourné, P. Monot, X. Davoine, A. Beck, B. Cros, G.Chériaux, … and many others…

Today's future is tomorrow's past



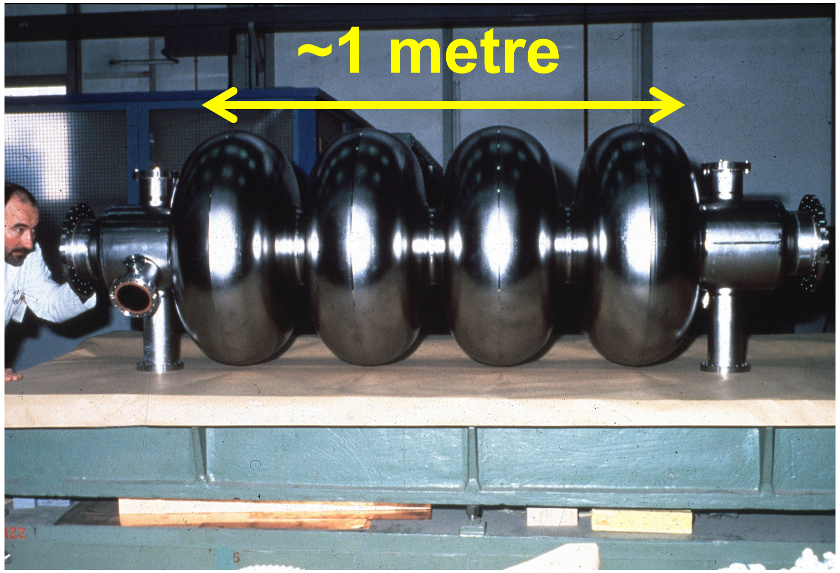


- energy = gradient × length ➔ bigger and bigger machines
- energy increase ➔ technologicale breakthrough

radiofrequency EM waves v/s plasma waves

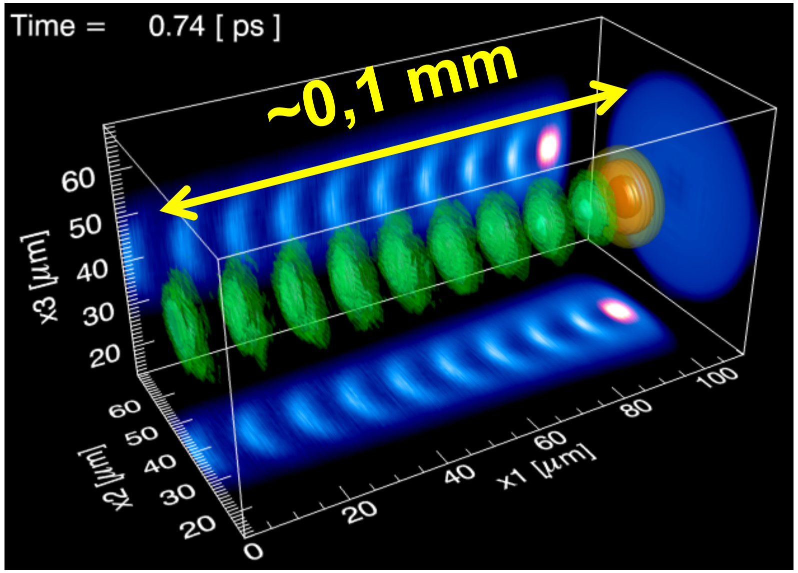
accelerating gradient [eV/m] = charge × long. electric field *(E_Z)*

resonator = RF cavity



$$E_z < 100\mathrm{MV/m}$$

resonator = plasma



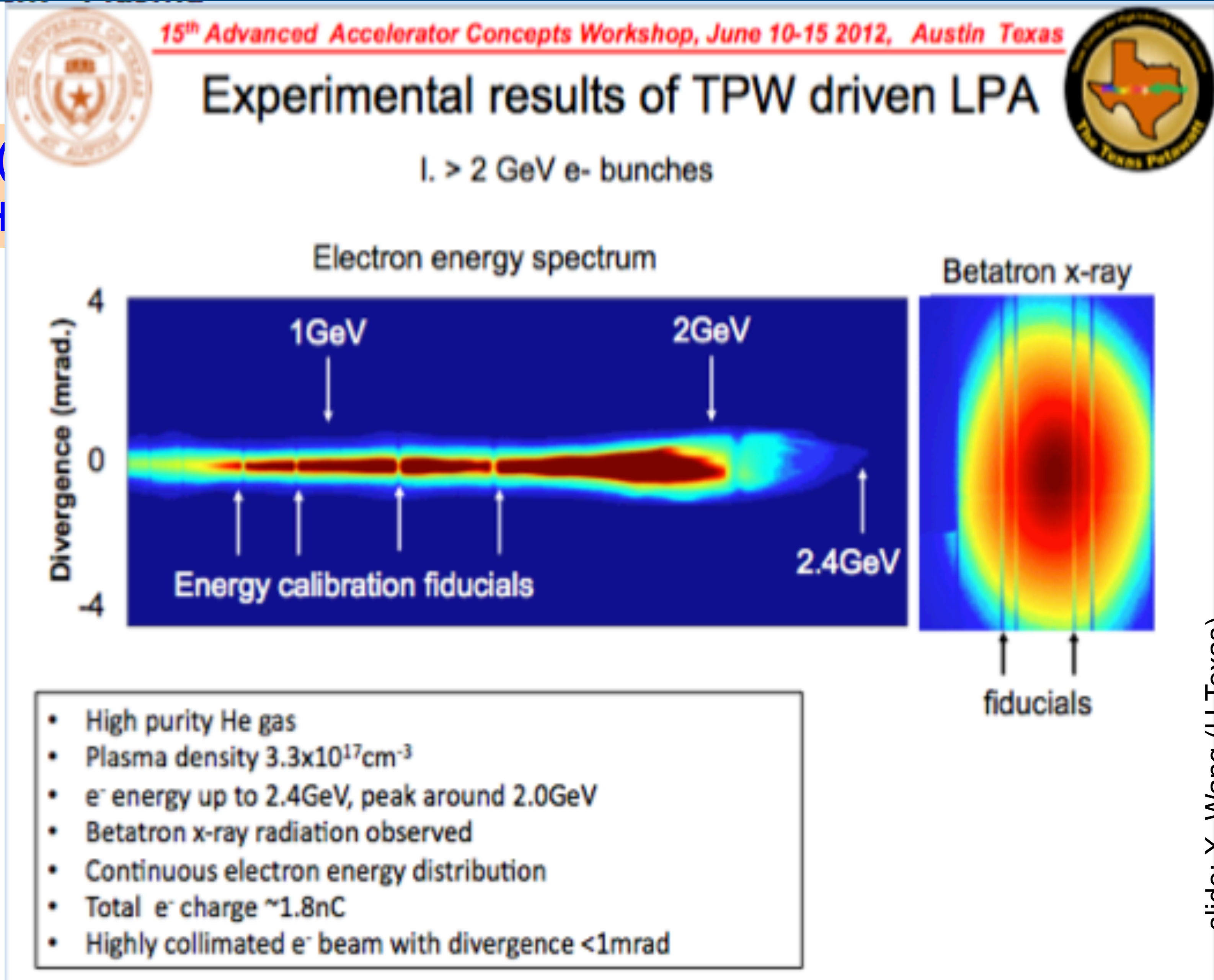
$$E_z = m_e c \omega_p / e \approx 100\mathrm{GV/m}$$

(for $n_e = 10^{19}$ cm^{-3})

long. electric field x 1000?

LWFA world record 2012 : ~2GeV in 7cm (U Texas Austin)

1 Petawatt (
plasma d'H



slide: X. Wang (U Texas)

present and future challenges for laser plasma accelerators

parameters of beam bunch:

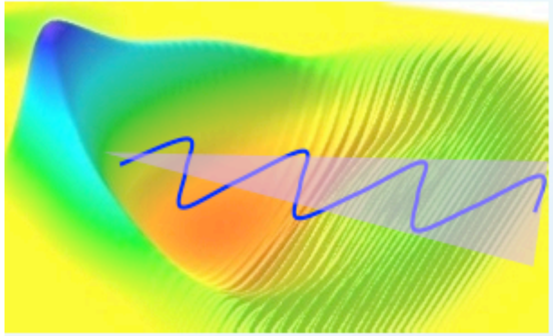
charge, ⟨position⟩, ⟨angle⟩, ⟨energy⟩, energy spread, transverse emittance, bunch duration

	LWFA	ILC	unit
❍ **increase energy**	0.2–1	250	GeV
➤increase acceleration length			
❍ **increase charge**	0.01–0.1	3	nC
➤ high gas density? external injection?			
❍ reduce bunch spacing	0.1–10	370.10^{-9}	s
➤laser rep. rate: “10Hz”, multi plasma-wave buckets?			
❍ **energy spread (“monochromaticity”)**	1%	0.1%	
❍ **bunch duration**	<1	300	µm
➤«*bane or blessing for colliders?*», difficult to measure			
❍ **transverse emittance**	0.1	19/0.07	mm.mrad

❍ **stability and control of *Q, x’,E*** (“reproducibility”)

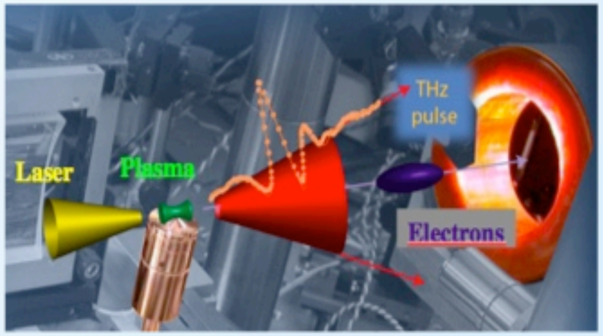
Applications: laser accelerated electrons for photons sources

Betatron radiation during acceleration – Multi keV



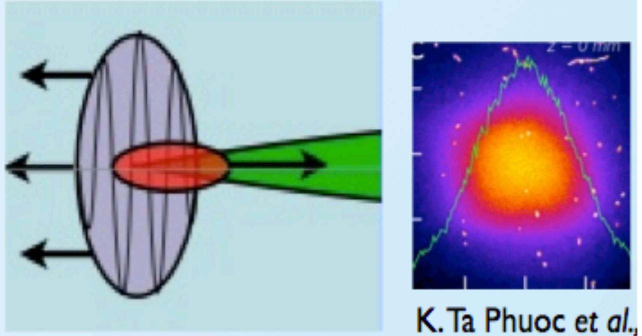
Rousse et al., Phys. Rev. Lett. 93, (2004)
Esarey et al., Phys. Rev. E 65, (2002)

Transition radiation from beam exiting plasma – MV/cm THz



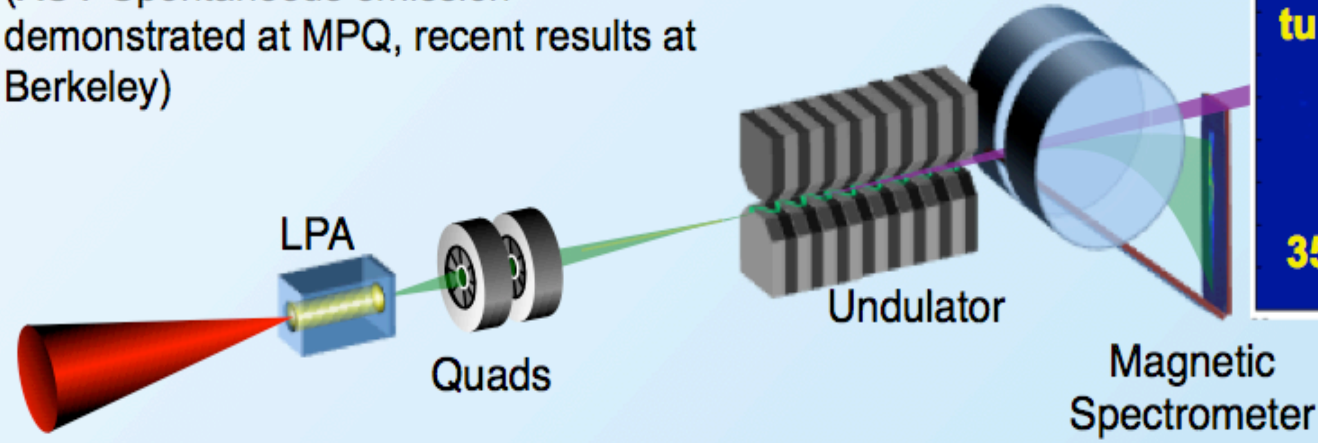
Leemans et al., Phys. Rev. Lett. 91, (2003)

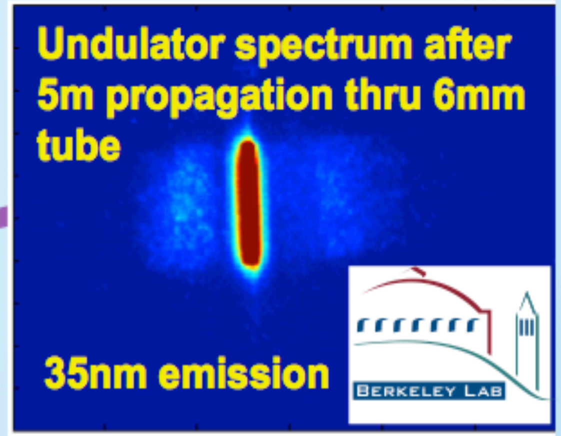
Thomson Scattering – Multi keV/ MeV x-ray/gamma ray



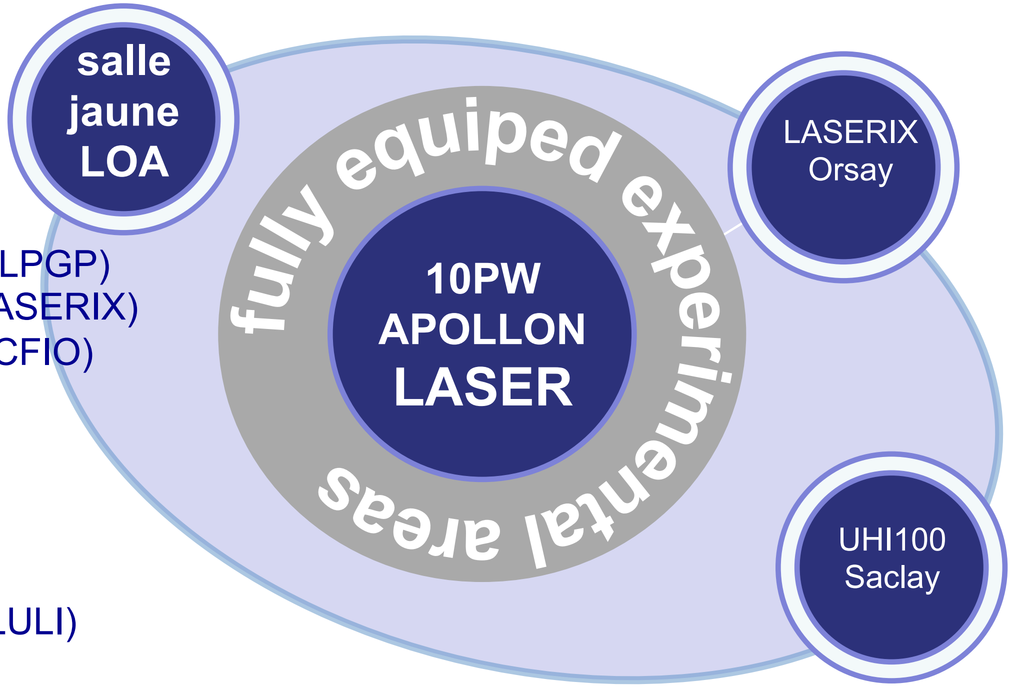
K. Ta Phuoc *et al.*, Nature Photonics (2012)

Free Electron Laser
(XUV Spontaneous emission demonstrated at MPQ, recent results at Berkeley)





Center open to national and international community

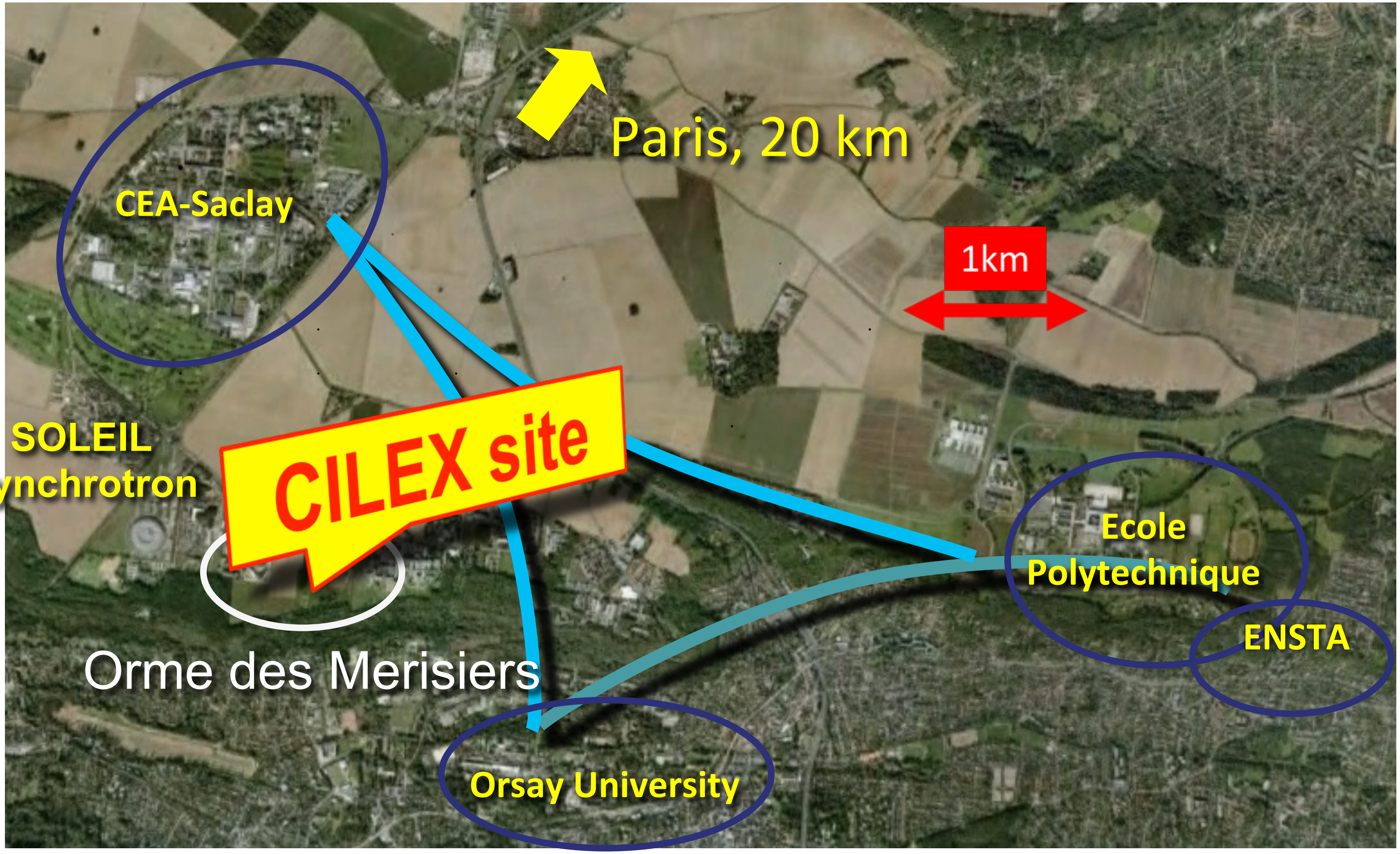


12 partner laboratories :

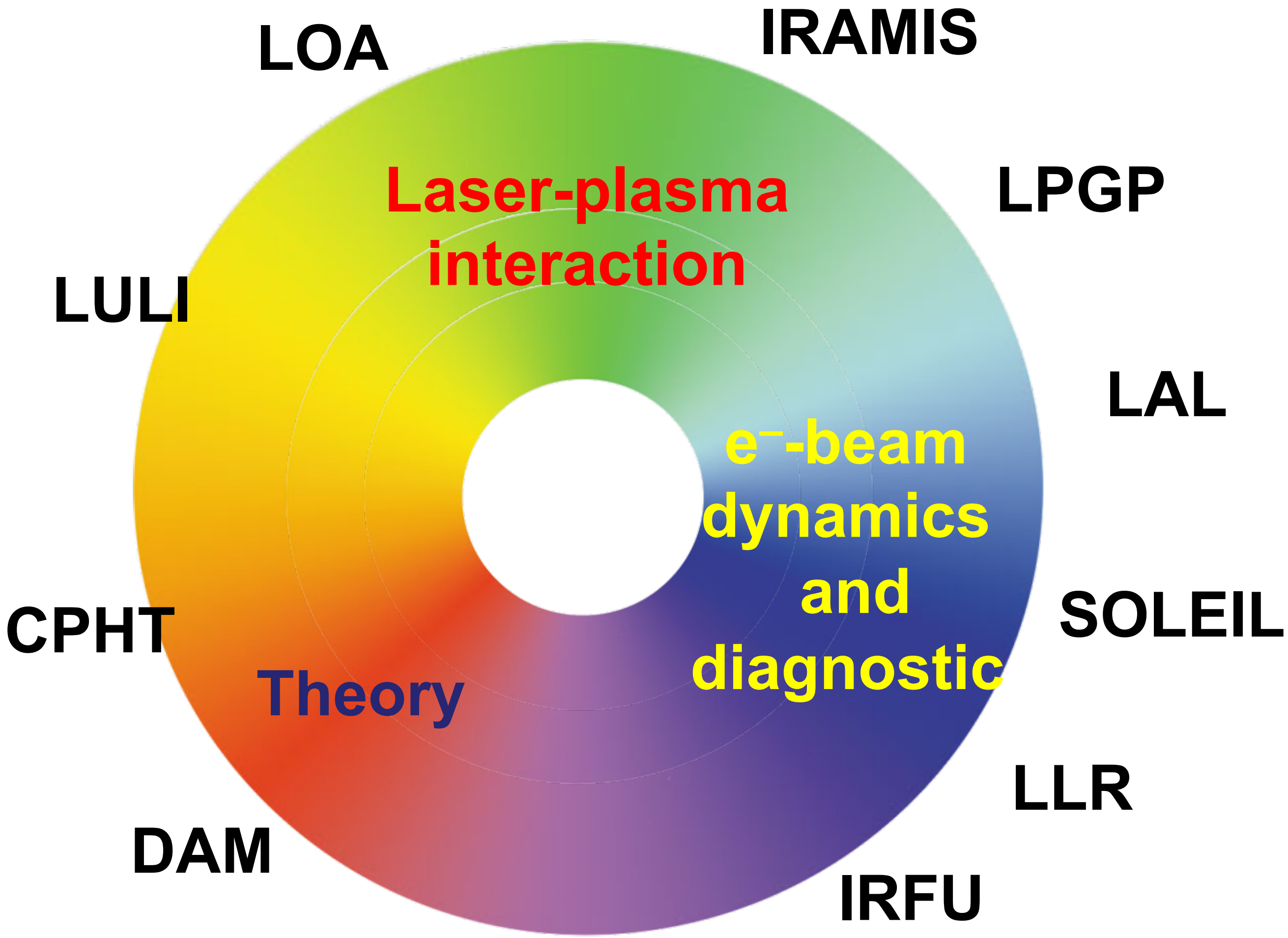
Laboratoire de Physique des Gaz et des Plasmas (LPGP)
Fédération Lumière Matière Fédération (LUMAT-LASERIX)
Laboratoire Charles Fabry de l'Institut d'Optique (LCFIO)
Laboratoire de l'accélérateur linéaire (LAL)
Synchrotron Soleil
Laboratoire d'Optique Appliquée (LOA)
Laboratoire Leprince-Ringuet (LLR)
Centre de Physique Théorique (CPhT)
Laboratoire pour l'Utilisation des Lasers Intenses (LULI)
Institut Rayonnement Matière de Saclay (IRAMIS)
Institut de recherche sur les lois fondamentales de l'univers (IRFU)
DSM Saclay

CILEX = APOLLON (20 M€) + BUILDING REHABILITATION + EXPERIMENTS INFRASTRUCTURE + SATELLITE FACILITIES (20 M€)

CILEX : dedicated to ultra-relativistic plasma physics



Large spectre de compétences scientifiques et de savoirs-faire technologiques



…ainsi que les industriels majeurs du domaine : sur le plateau de Saclay

CILEX/APOLLON design requirements

science topics and applications

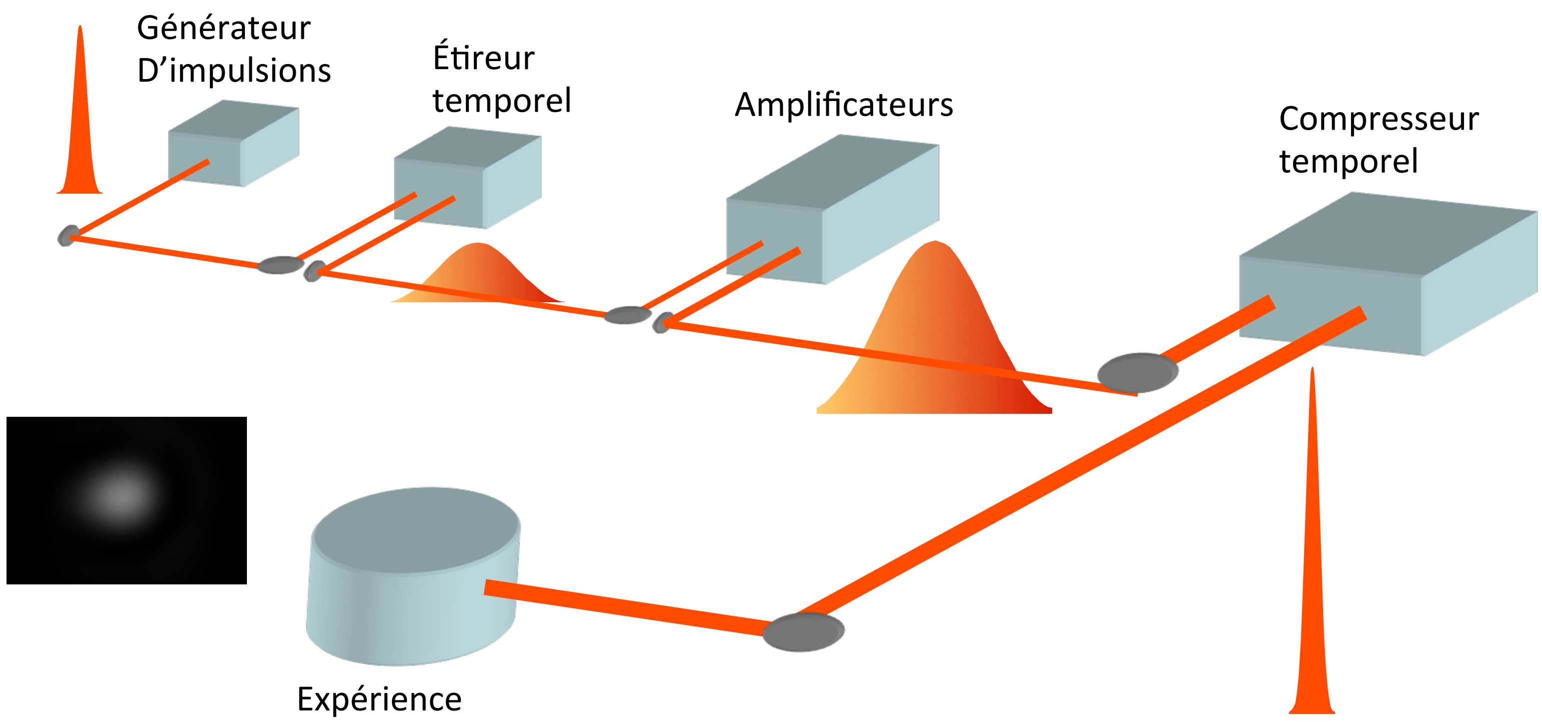
- ❍ Laser plasma electron acceleration
- ❍ Laser plasma ion acceleration
- ❍ Laser plasma x-ray sources

- ❑ high laser intensity: **$I > 10^{22}$W/cm^2 ($a_0 = (0.85\ (I_{18}\lambda^2)^{\wedge 0.5}) > 100$**
- ❑ multiple laser beams
  - – pump-probe experiments
  - – multi stage laser acceleration
- ❑ high repetition rate
  - – 1 shot per min at full energy
  - – alignment (10Hz) and optimization (0.1Hz) at reduced energy
- ❑ high contrast (control/minimize preformed plasma)
- ❑ reliability and stability of well characterized beams
- ❑ dedicated yet flexible experimental set up

Chirped pulse amplification: Highest peak powers

- **1985: principle of CPA in optical domain demonstrated** (Strickland&Mourou)

  Compression of amplified chirped optical pulses, Opt. Com., Vol 56, number 3, 1 December 1985

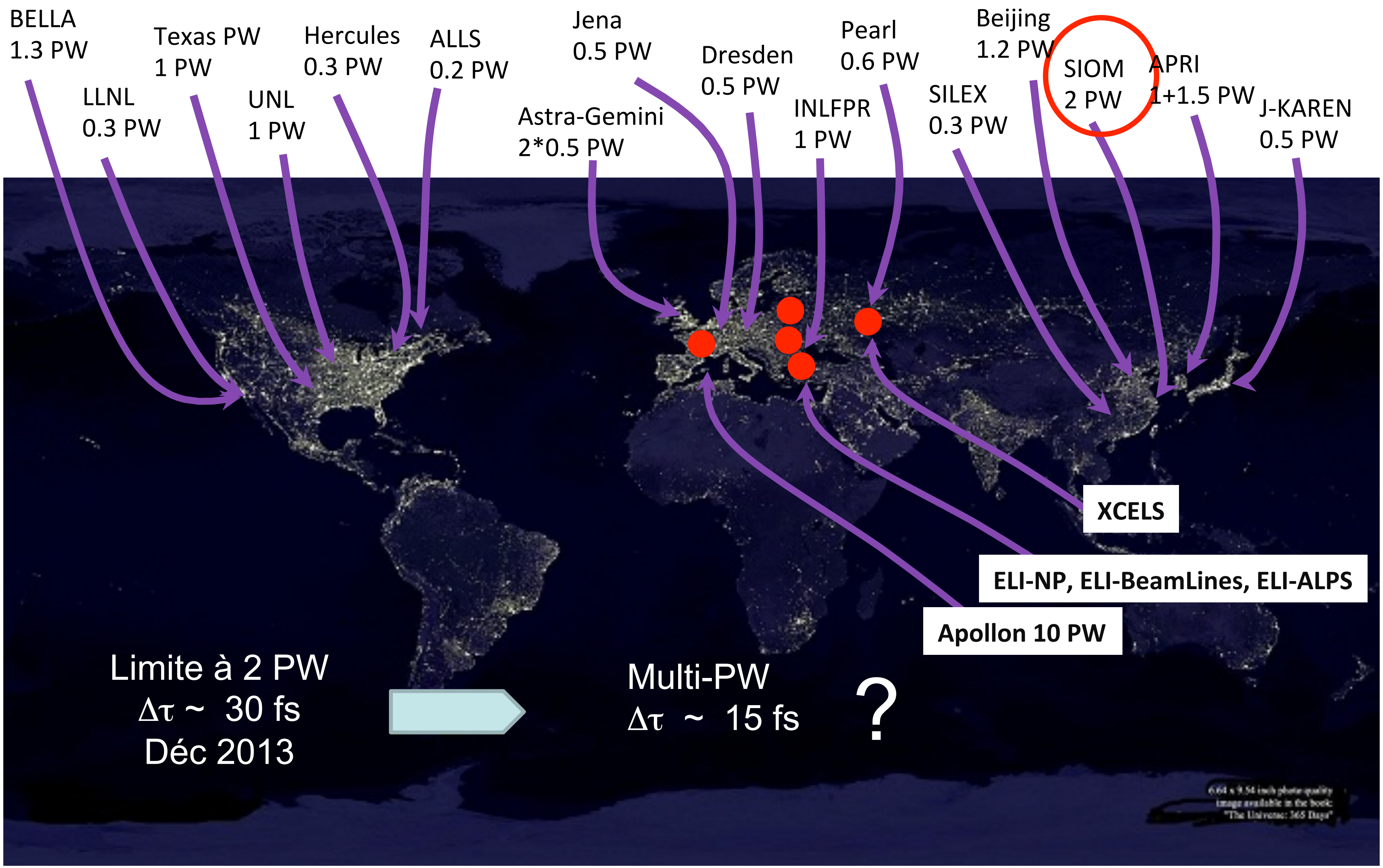


- **simple scheme …**

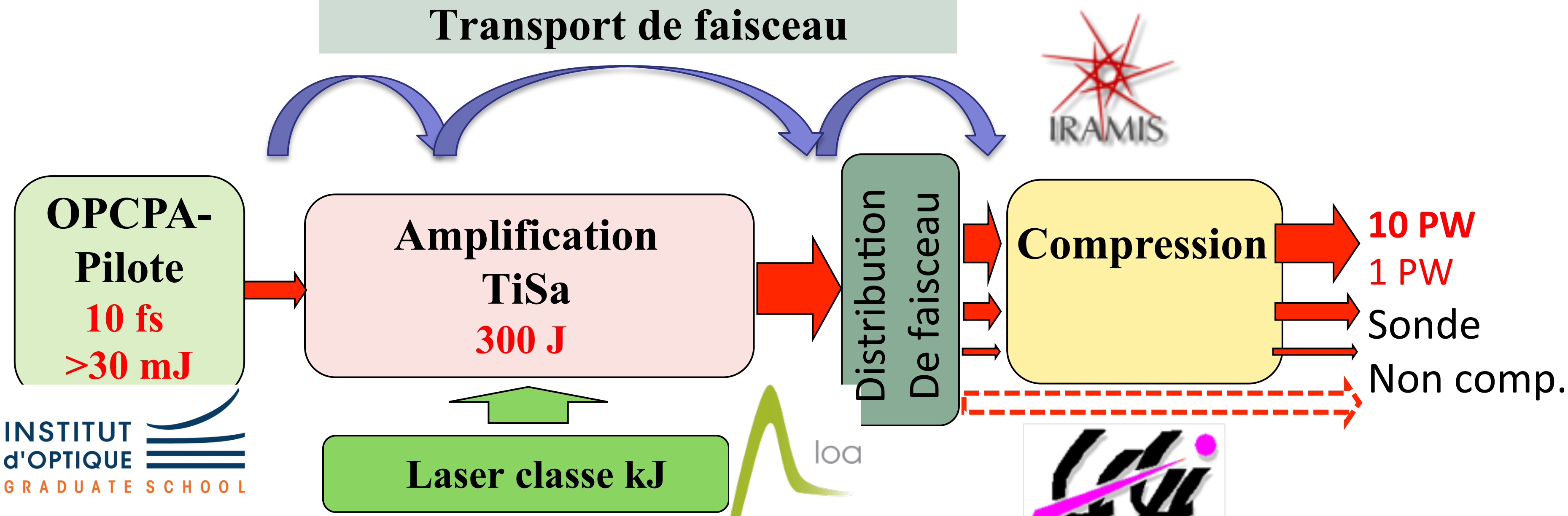
  …hiding complications at highest energies and shortest pulse durations

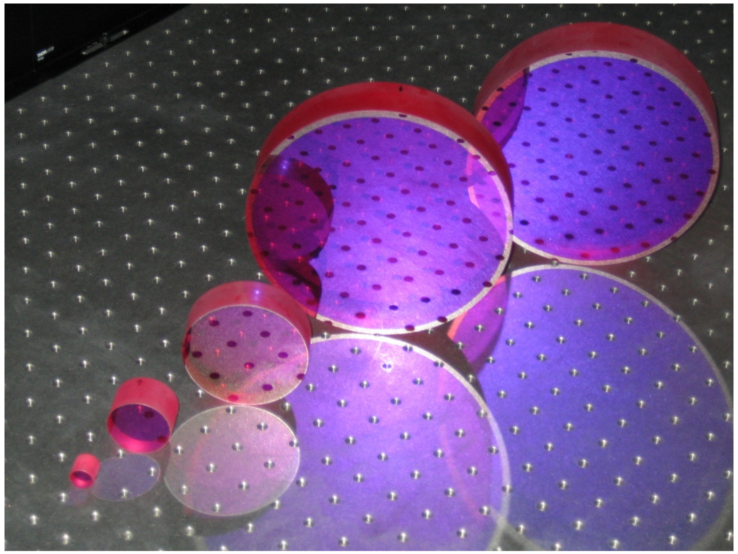
slide courtesy of G Cheriaux

Systems with potential intensities above 10^{20} - 10^{21} W/cm²



slide courtesy of G Cheriaux

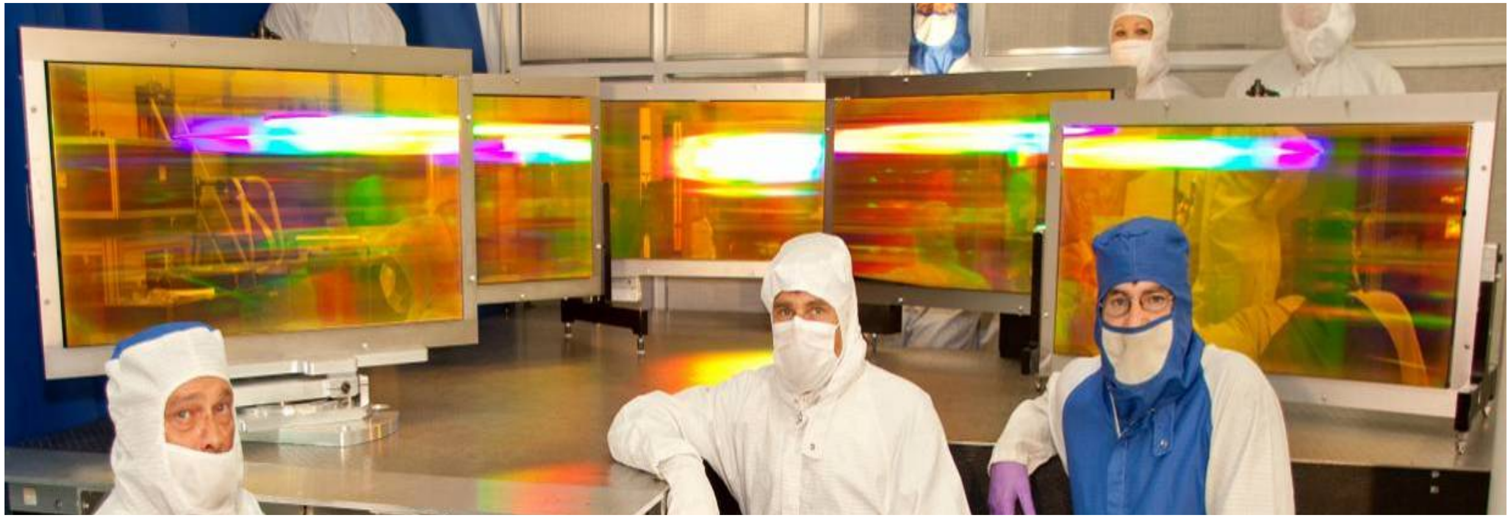


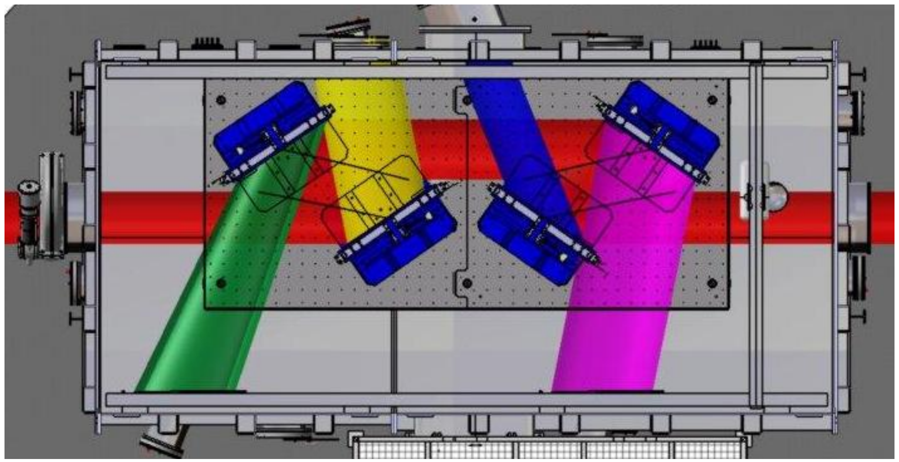


Cristaux de TiSa : GT-AT
de 15 mm à 175 mm
Absorption: 93%

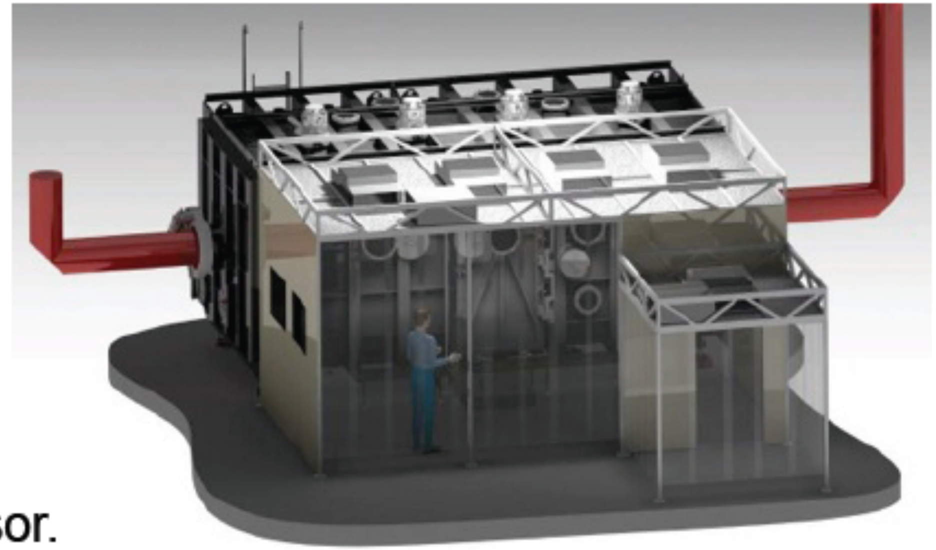
slide courtesy of G Cheriaux

Pulse compression: four 900x450 cm² diffraction gratings in vacuum



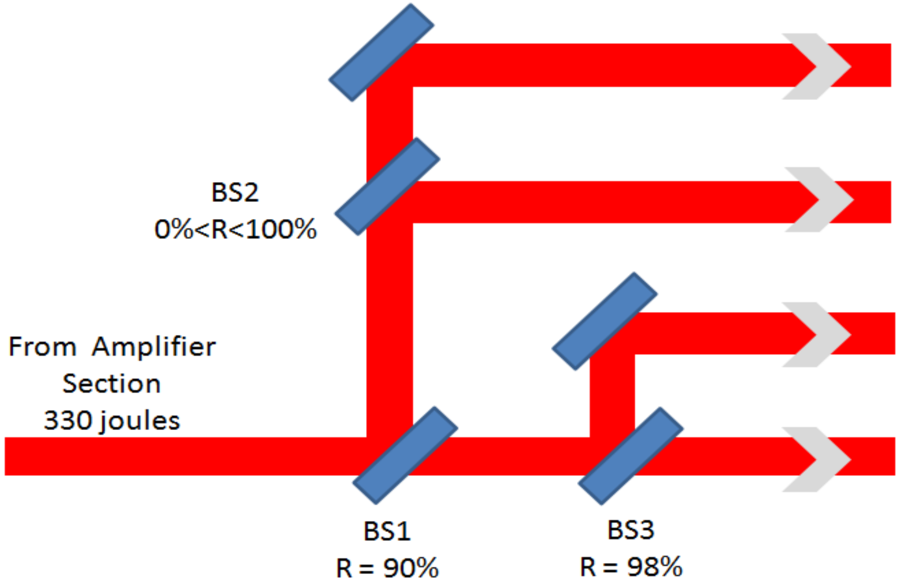


ɩor.



APOLLON laser beams

❍ 4 independent beams, discrete pulse energies



10PW:15fs-few ps / 150J,75J,50J,25J

ns beam: uncompressed 200J

1PW: 15fs-few ps / 15J,10J,5J, 1J

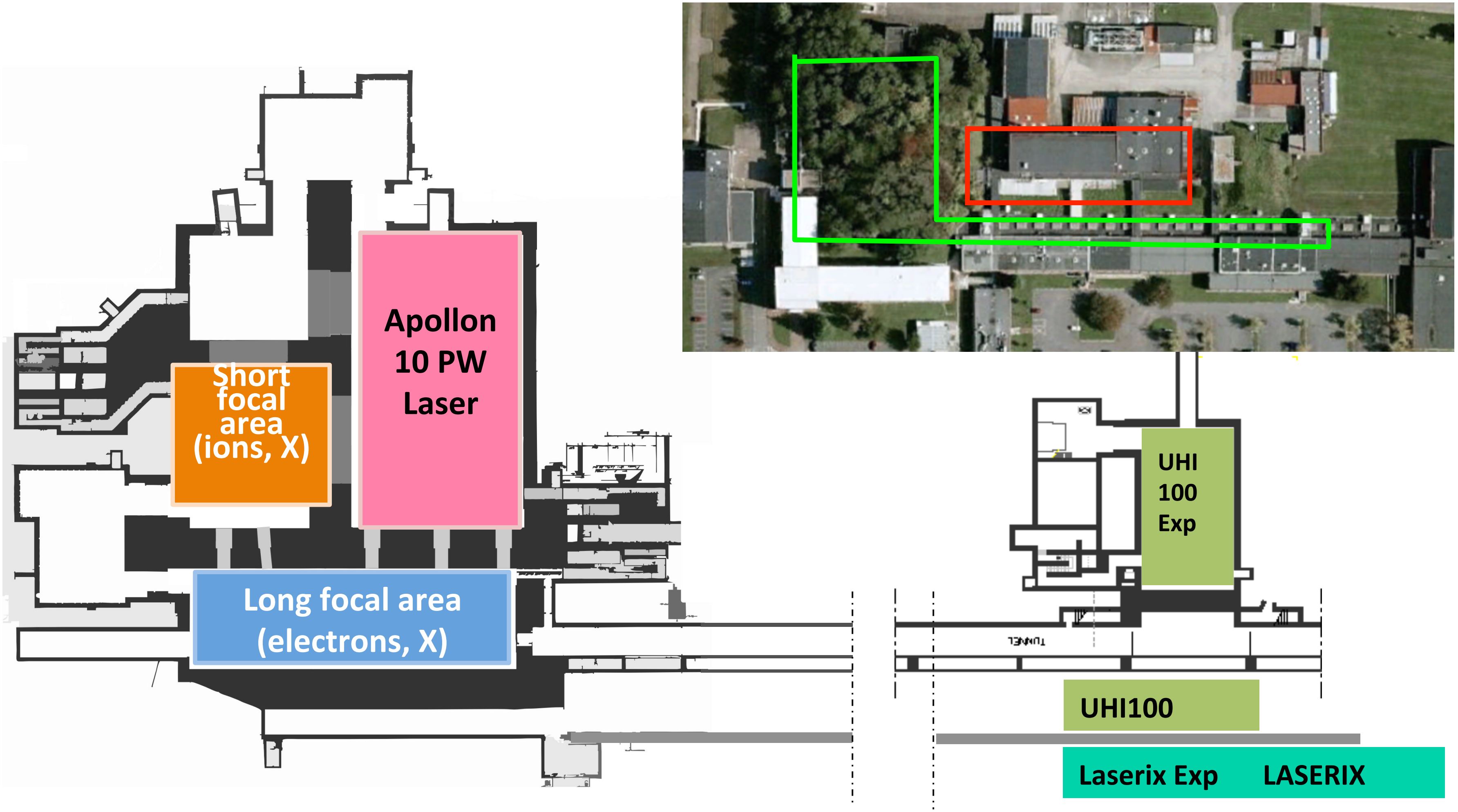
probe: <20fs / 250mJ

- Beam pointing and stability
  - alignment on target (absolute): 1 focal spot size
  - alignment on target (relative): < 20% of focal spot size
- Synchronisation
  - delay line range ± 5ns for each
  - synchronization to < 30% of pulse duration (later <10%)
  - time step of delay < 20% of pulse duration (later <10%)

Site « l'Orme des Merisiers » (next to SOLEIL synchrotron)

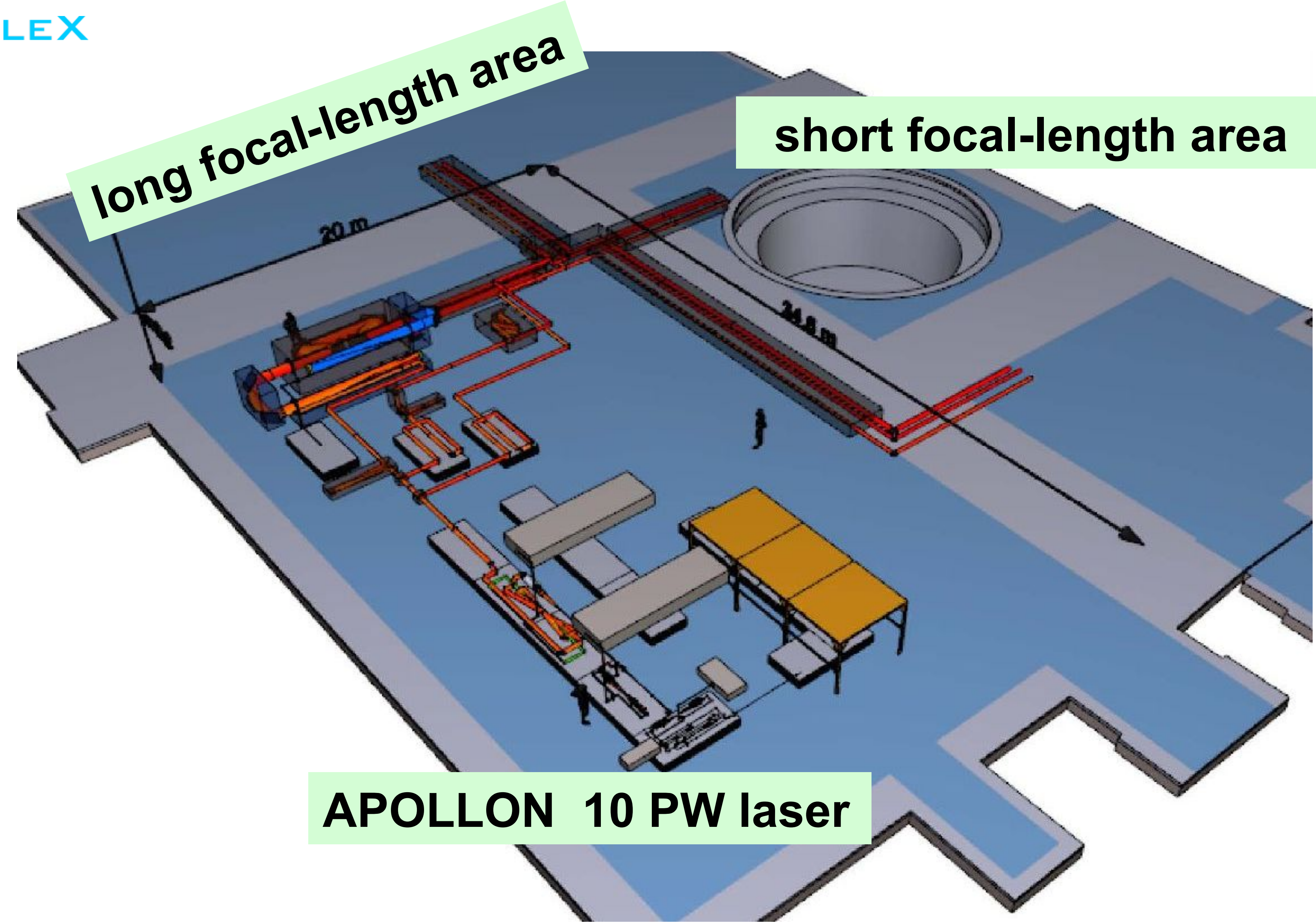
- ❑decommissioned e⁻ – linac building fully dismantled in 2006 (property: CEA)
- ❑renovation until end 2013: 5000m² total,

  2 radiation-protected experimental areas



CILEX-APOLLON = (lasers 1PW+10PW) x 2 zones experimentales

CILEX



1 laser, 2 distinct fully-equipped rad-protected exp. halls

HE1 : short focals

- **ion acceleration**
- **HHG, flying mirror, Xray laser (solid, gas)**
- **high-field physics (solid, gas, vacuum)**
- **mainly solid targets**
- **short focals : *f=1–5 m***
- **extreme intensity: a_0≈*10–10000***
- **t contrast : ultimate**

HE3 :APOLLON LASER

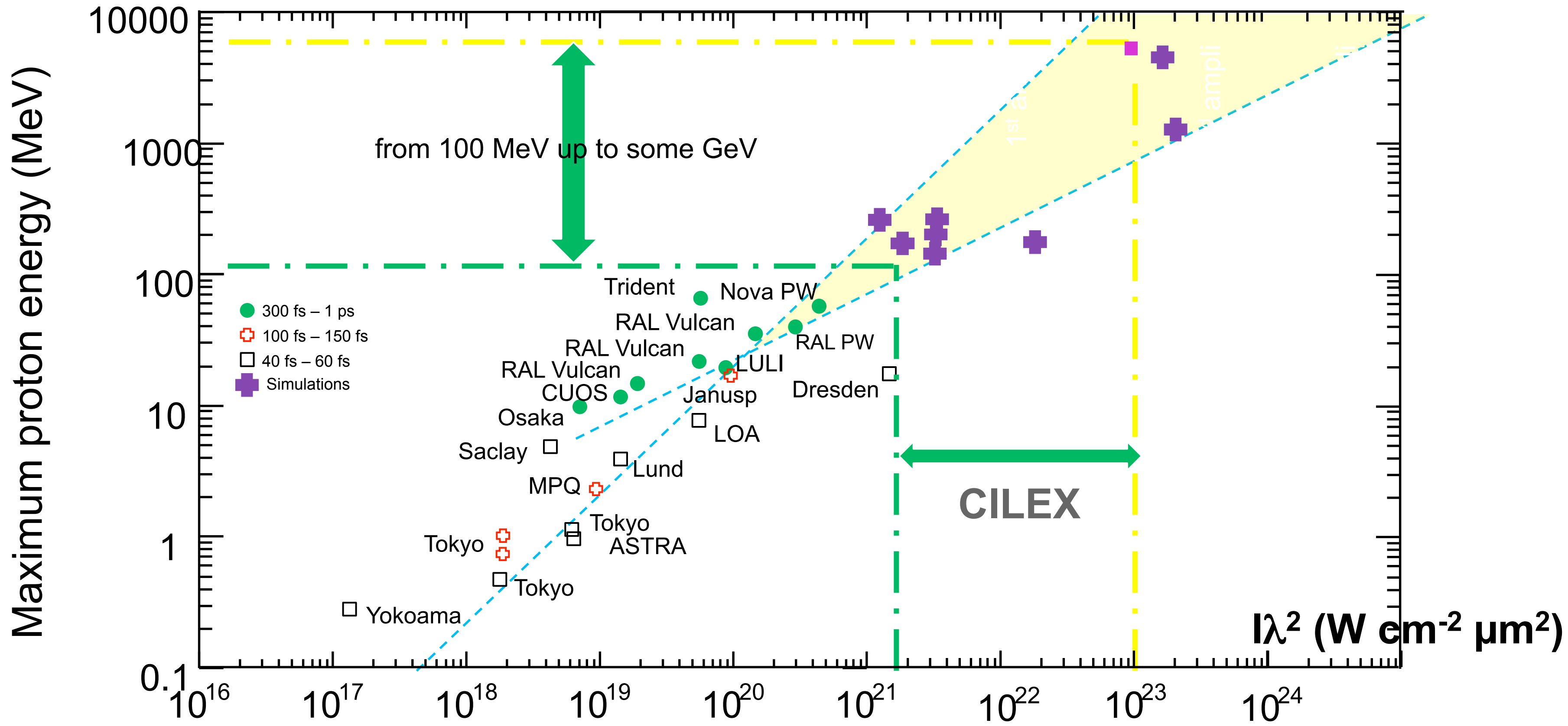
- **pump1: 15fs-qq ps/ 150J-25J Ø400**
- **pump2: 15fs-qq ps/ 15J-2J Ø400**
- uncompressed 200J-0
- probe: 15fs 0.2-1J

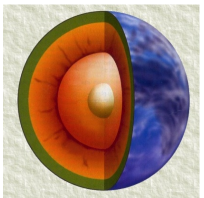
HE0 : long focals

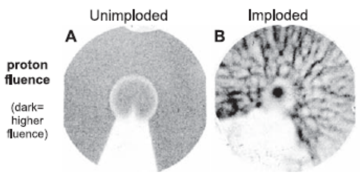
- **electron acceleration**
  - single stage and multi-stage (2)
  - blow-out and quasi-linear regime
- **direct photon production**
  - plasma undulator («betatron»)
  - magnetic undulator radiation (seeding)
  - non-lin. Thomson; Compton up-scattering
- **HHG, flying mirror** (on gas targets)

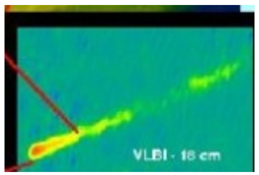
- **gaseous targets**
- **longest focals : *f=10–20 m***
- **modest intensity: a_0≈*1–10***
- **t contrast: excellent (but not ultimate)**

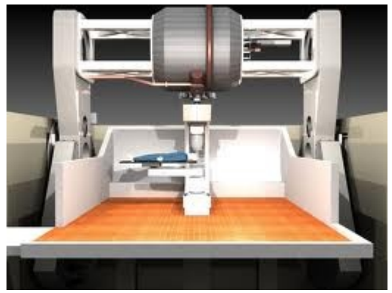
Ion acceleration: access proton energies O(1GeV)



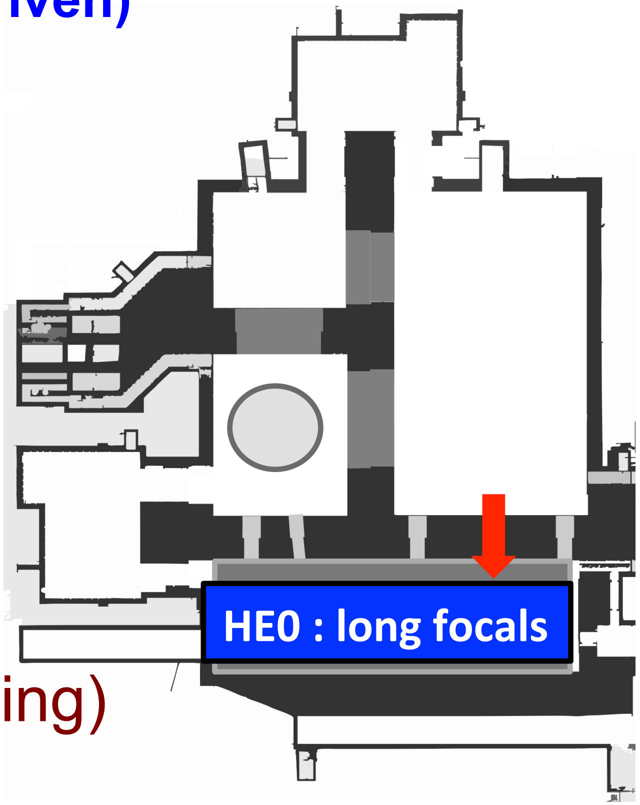








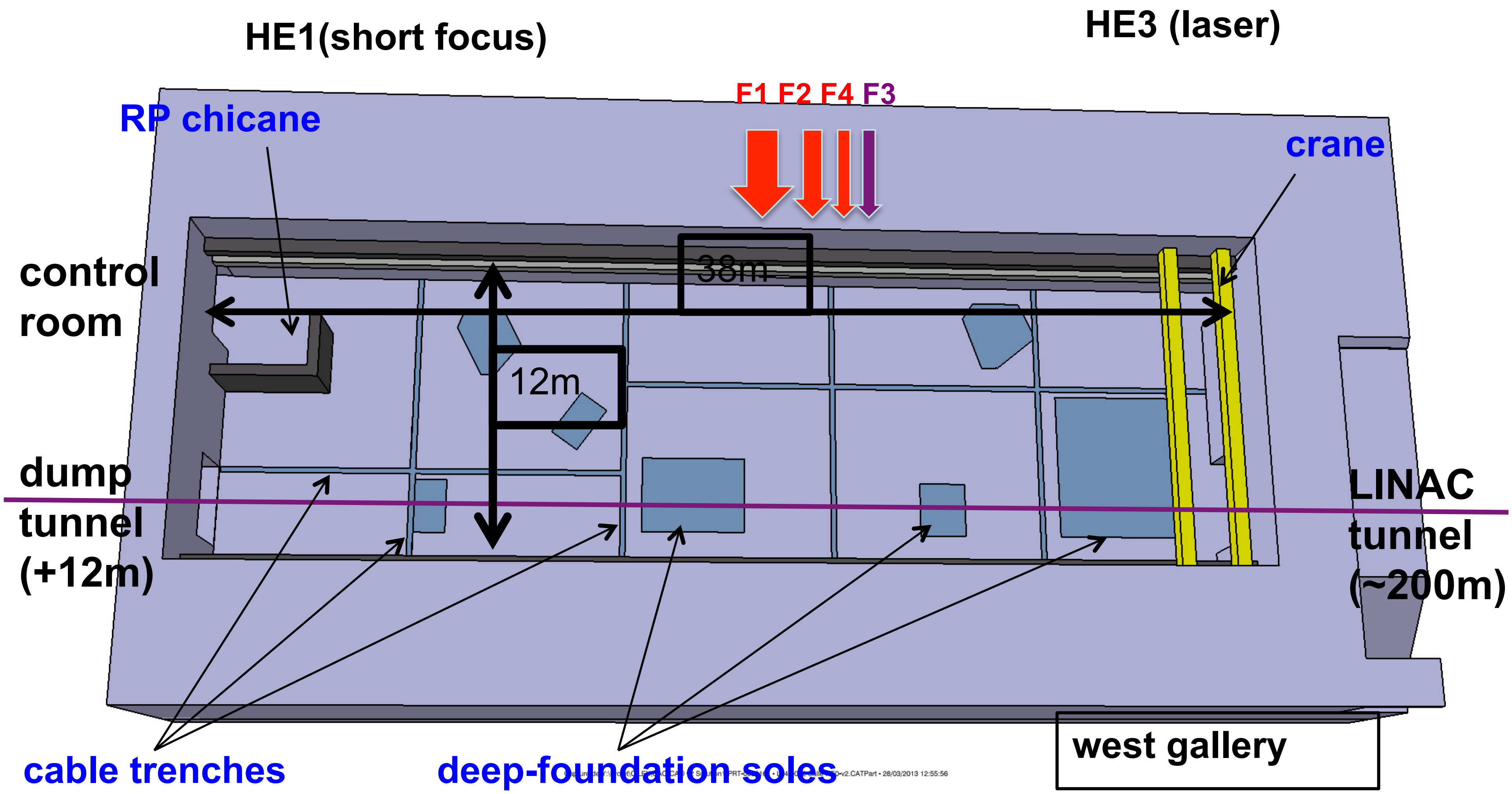
- ❍ **investigate validity of LWFA for future high energy accelerators**
- ❍ **investigate plasma wave acceleration relevant for alternative excitation (e.g. PWFA either e– or proton driven)**



38mx12m

- **electron acceleration**
  - single stage and multi-stage
  - blow-out and quasi-linear regime
- **direct photon production**
  - plasma undulator («betatron»)
  - magnetic undulator radiation (seeding)
  - non-lin. Thomson; Compton up-scattering
- **HHG, flying mirror** (on gas targets)

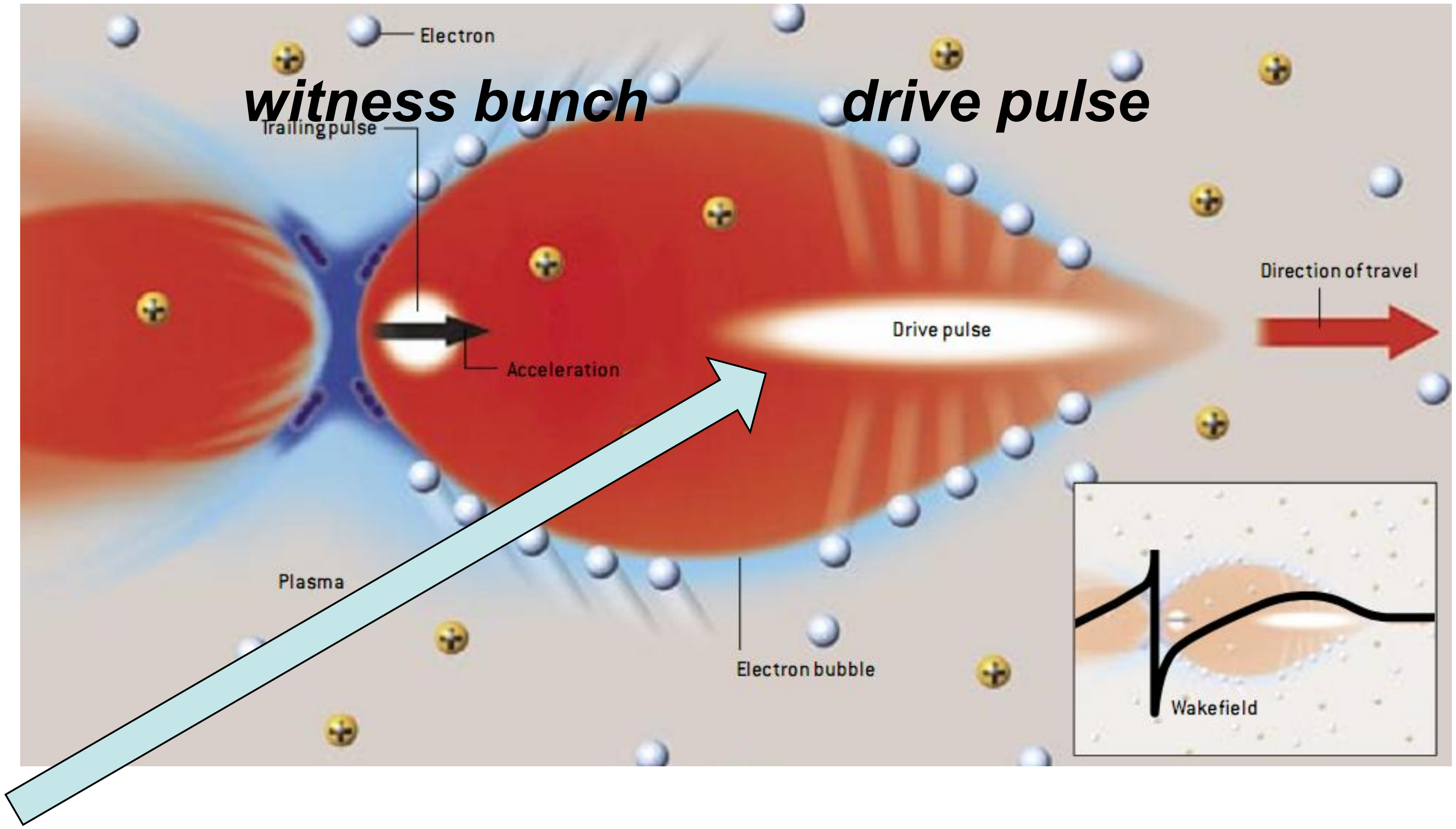
Experimental Hall HE0



for the 1st two years of CILEX operation as stated in "Scientific Case"document

- ***Validate the specifications of the PW laser beam through the mechanism of laser plasma acceleration in the bubble regime***
  - **$I_0 \geq 10^{20}$ W/cm^2 O(1-5GeV)**
  - **(static) gas cell or (pulsed) gas jet, O(10^{19}cm^{-3}) H_2 or He**
  - **F2 beam (15 J, 15 – 200 fs, Ø=40 mm)**
- ***Develop a two-stage laser plasma accelerator – injector and accelerator***
  - **injector = F2 beam (15 J, 15 – 200 fs, Ø=140 mm)
    (static) gas cell or (pulsed) gas jet, 10^{19}cm^{-3} H_2 or He
    with density gradient taylored, or high Z ionization**
  - **accelerator = F1 beam(15 J-75J, 15 fs – 1 ps, Ø=400 mm)
    gas cell, gas filled capillary (up to 1 meter!)**

Laser wakefield acceleration with self-injection

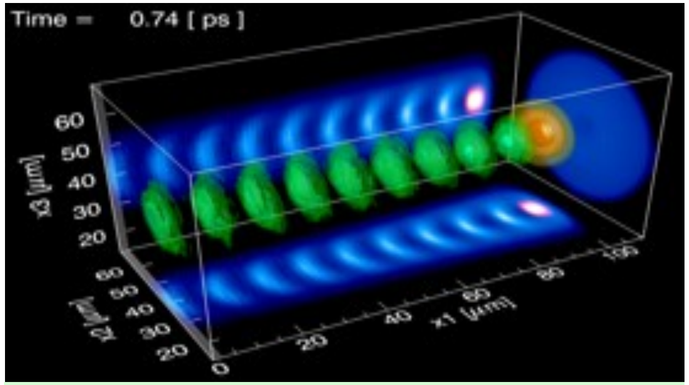


- laser pulse (fs), 100TW – Petawatt: LOA, Berkeley, CILEX,...
- very short electrons (or positrons) bunches: SLAC, DESY, Frascati
- proton bunches: CERN (SPS,LHC)

High gradient acceleration by laser wakefields (LWFA)

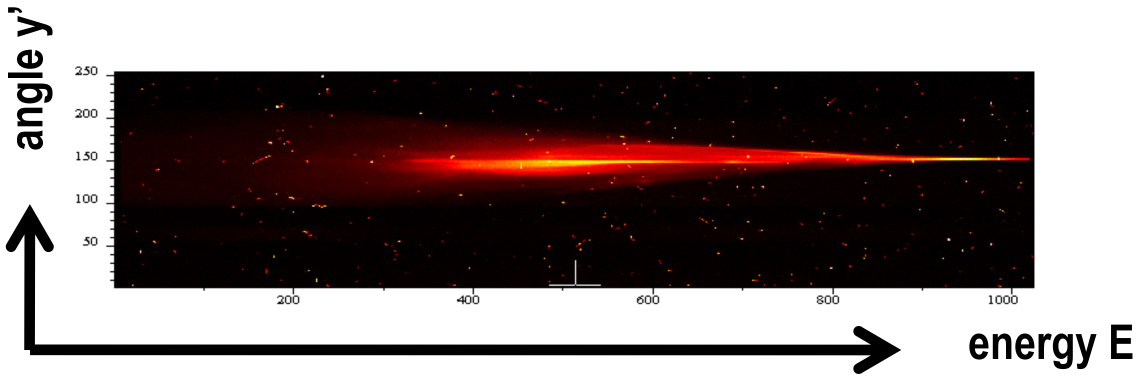
→ reduce size of accelerating structures

$E_z < 100\,\mathrm{MV/m}$

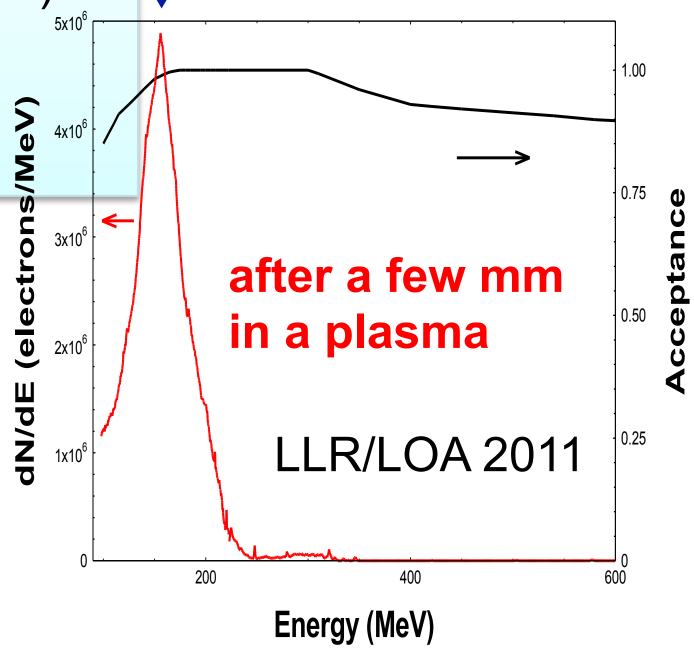


$E_z = m_e c \omega_p / e \approx 100\,\mathrm{GV/m}$

- à ppresent technology: TiSaph lasers O(100TW, 30fs)
- electron acceleration from 0 to O(200MeV) (even 2GeV)
- energy spread: a few percent
- bunch charge: 10pC-1nC
- normalised RMS emittance O(2mm.mrad)



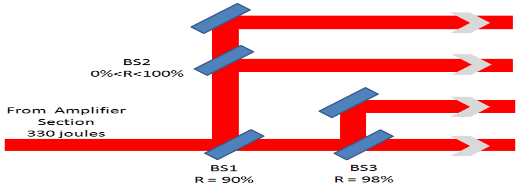
5.10^6 e⁻/MeV
à 150 MeV



Scaling laws of wakefield acceleration

Courtesy of Xavier Davoine

Faisceau « 1 péta-Watt»



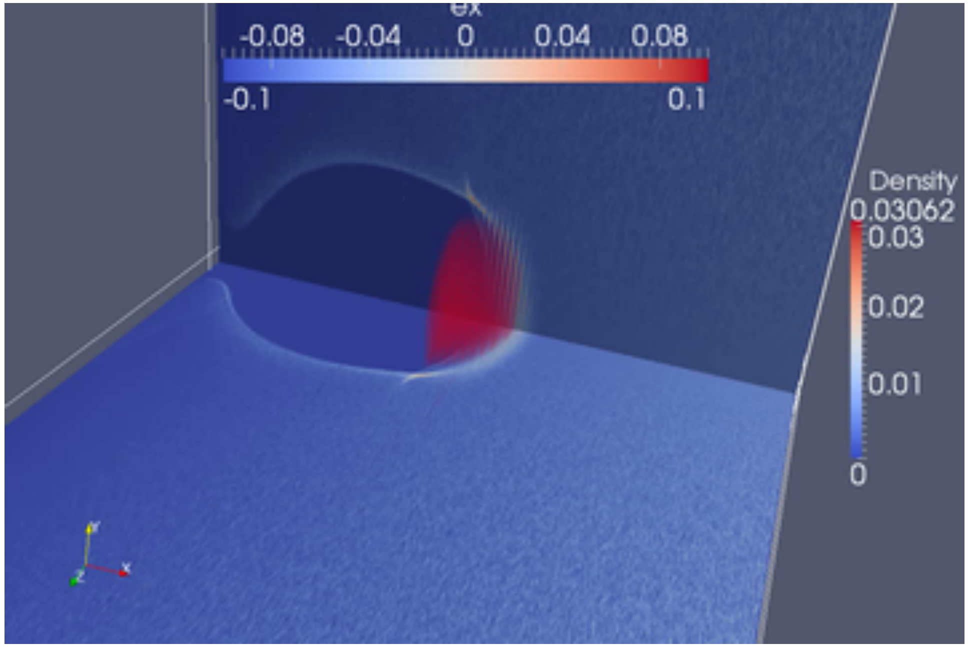
Faisceau « 5 péta-Watt»

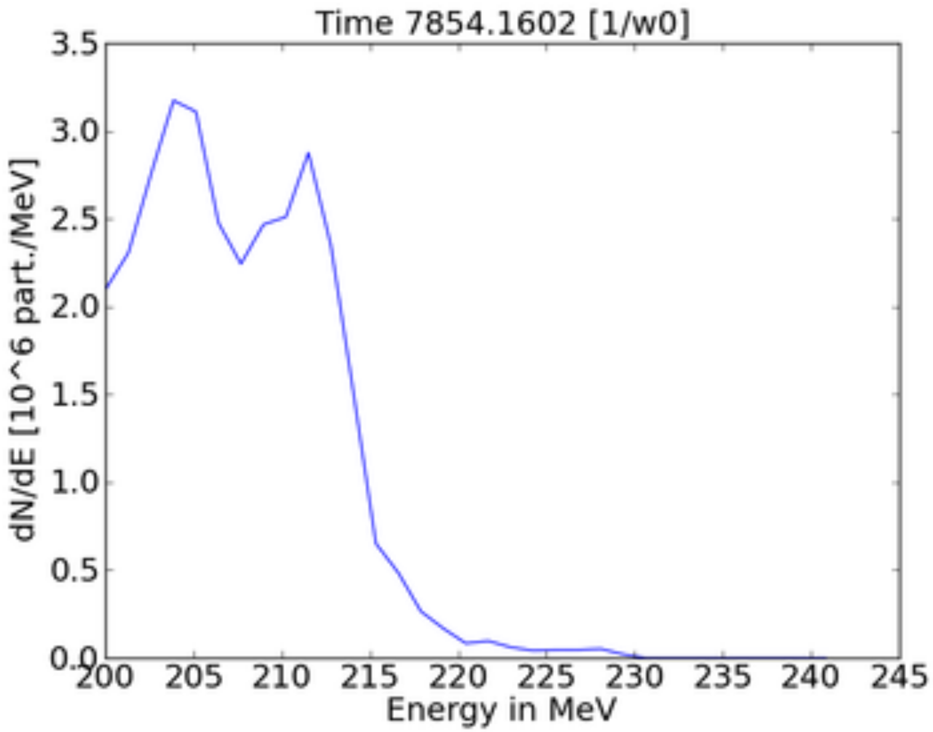
F2 – 15 J		F1 – 75 J	
Short pulse	**Long pulse**	**Short pulse**	**Long pulse**
High Charge	**High Energy**	**High Charge**	**High Energy**
$\tau 0$ = 15 fs	$\tau 0$ = 40 fs	$\tau 0$ = 15 fs	$\tau 0$ = 68 fs
w0 = 6.4 µm	w0 = 25.5 µm	w0 = 6.4 µm	w0 = 43 µm
a0 = 26	a0 = 4	a0 = 58	a0 = 4
P0 = 1 PW	P0 = 350 TW	P0 = 4.7 PW	P0 = 1 PW
$n_e = 1.3 \times 10^{19}$ cm^{-3}	$n_e = 7 \times 10^{17}$ cm^{-3}	$n_e = 2.8 \times 10^{19}$ cm^{-3}	$n_e = 2.5 \times 10^{17}$ cm^{-3}
E = 0.65 GeV	**E = 3.5 GeV**	**E = 1.45 GeV**	**E = 10 GeV**
Q = 4.3 nC	Q = 0.7 nC	Q = 10 nC	Q = 1.3 nC
L_{acc} = 0.7 mm	L_{acc} = 3.2 cm	L_{acc} = 0.7 mm	L_{acc} = 15 cm

Simulation of 600TW 25fs selfinjection & acceleration (CILEX startup)

propagation of laser pulse
in co-moving window (18mm)
bubble shrinkage and expansion

evolution of energy spectrum





stable acceleration over long distances -> choice of regime
narrow electron spectrum with O(3GeV) energy gain over O(20mm)

Arnaud Beck

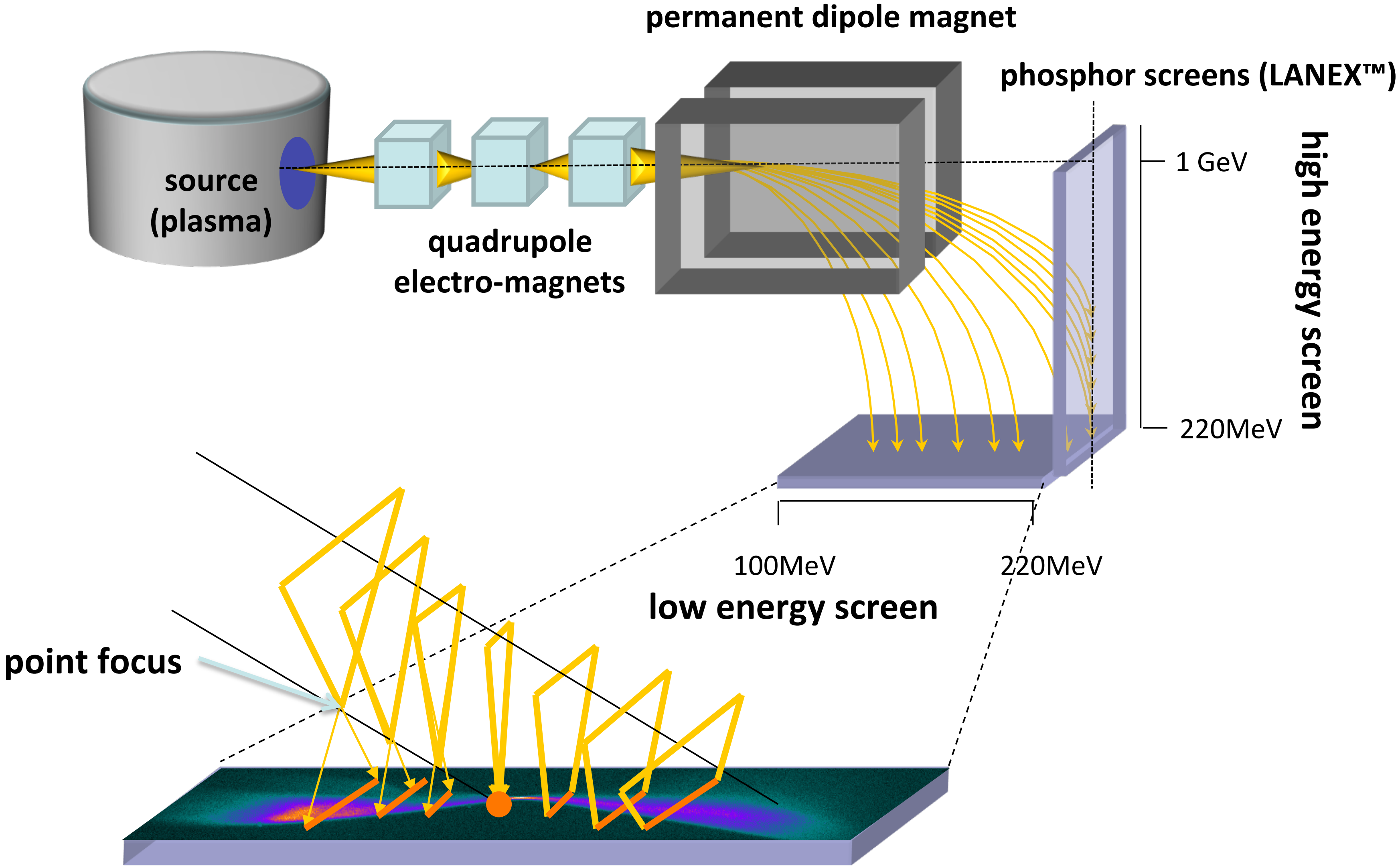
Diagnostics

- **electrons:**

  parameters of beam bunch: moments in 6D phase space....
  charge, ⟨position⟩, ⟨angle⟩, ⟨energy⟩, energy spread, transv. emittance, bunch duration

  - **low bunch rates + strong shot-to-shot fluctations expected**
  - **accomodate wide range of parameter values to be measured**
  - **need a complete (as possible) shot-by-shot bunch characterization between each plasma acceleration stage**
  - **non- or less destructive diagnostics first, destructive ones later**
- **Xrays («betatron» radiation)**
  - **cohabitation with e-diagnostic -> requires electron bend**
  - **long stand-off distances for energy spectrum measurement?**
- **laser & plasma diagnostics**
  - **side view and top view of plasma**
    (probe beam F4 and/or "hole beam")
  - **laser post-mortem diagnostics**

focussing electron spectrometer LLR/LOA



Scientific Goals for Long focus Area

for the 1st two years of CILEX operation as stated in "Scientific Case"document

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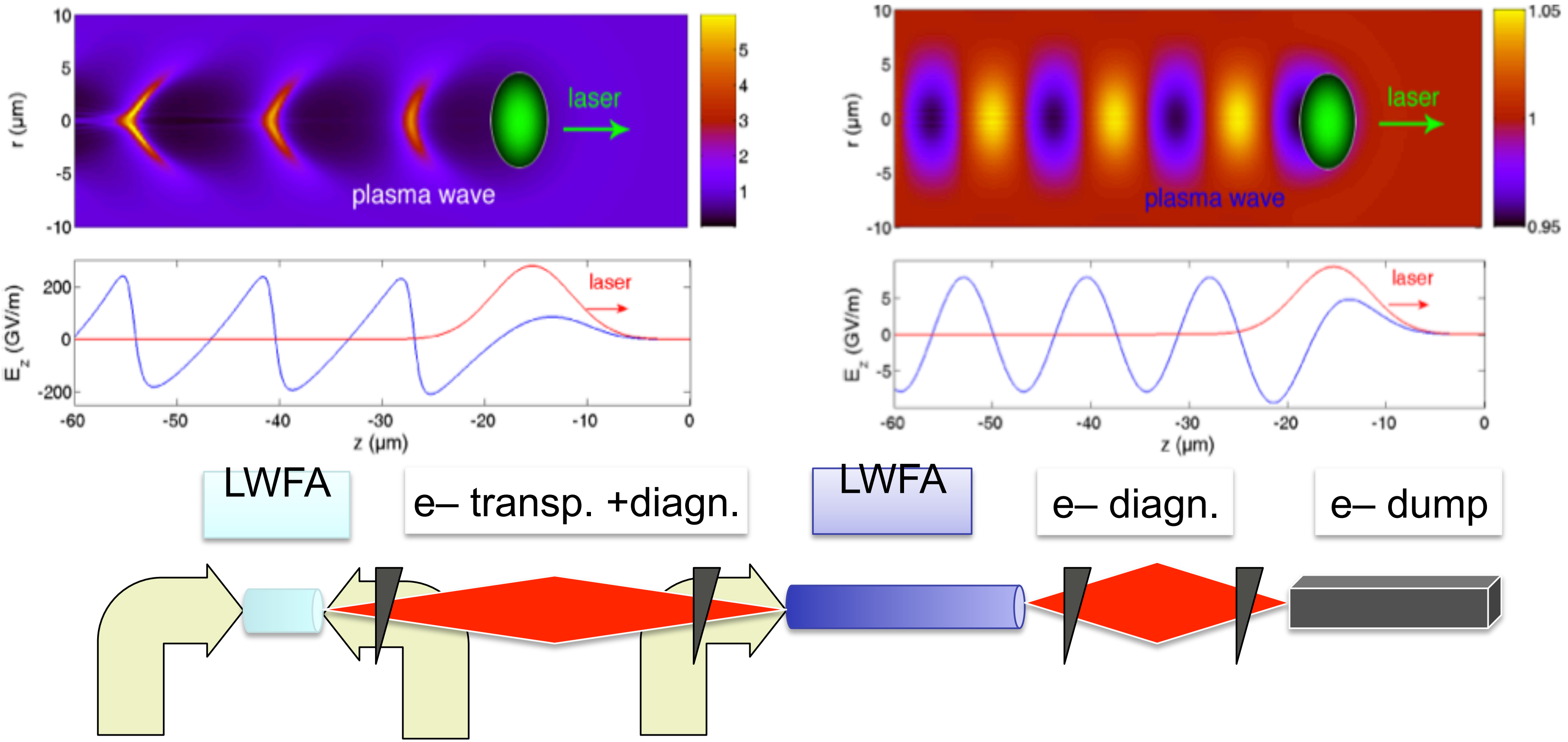
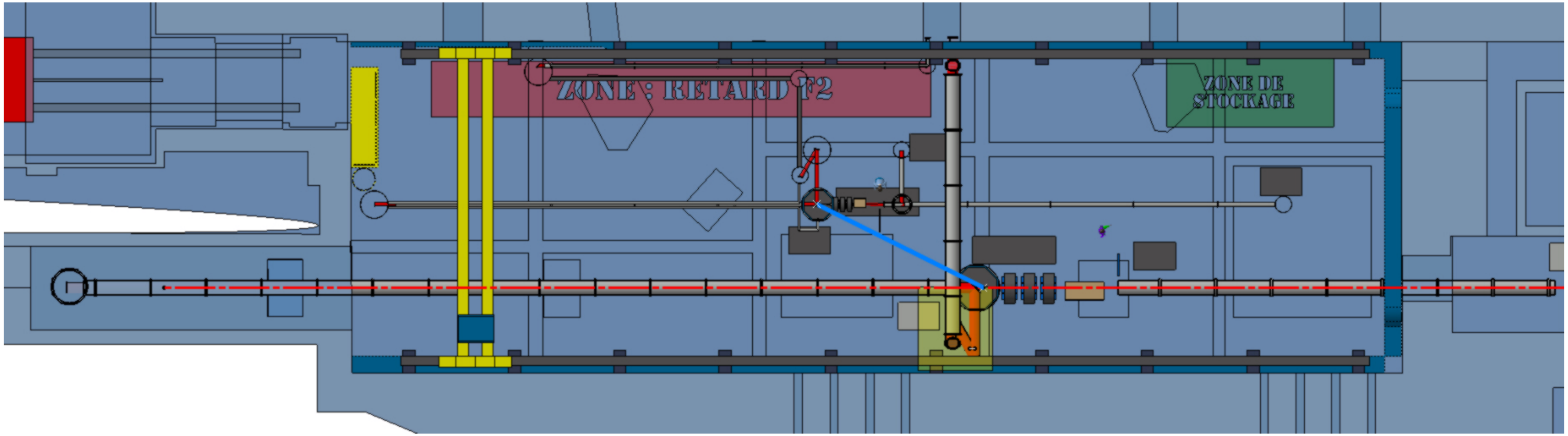
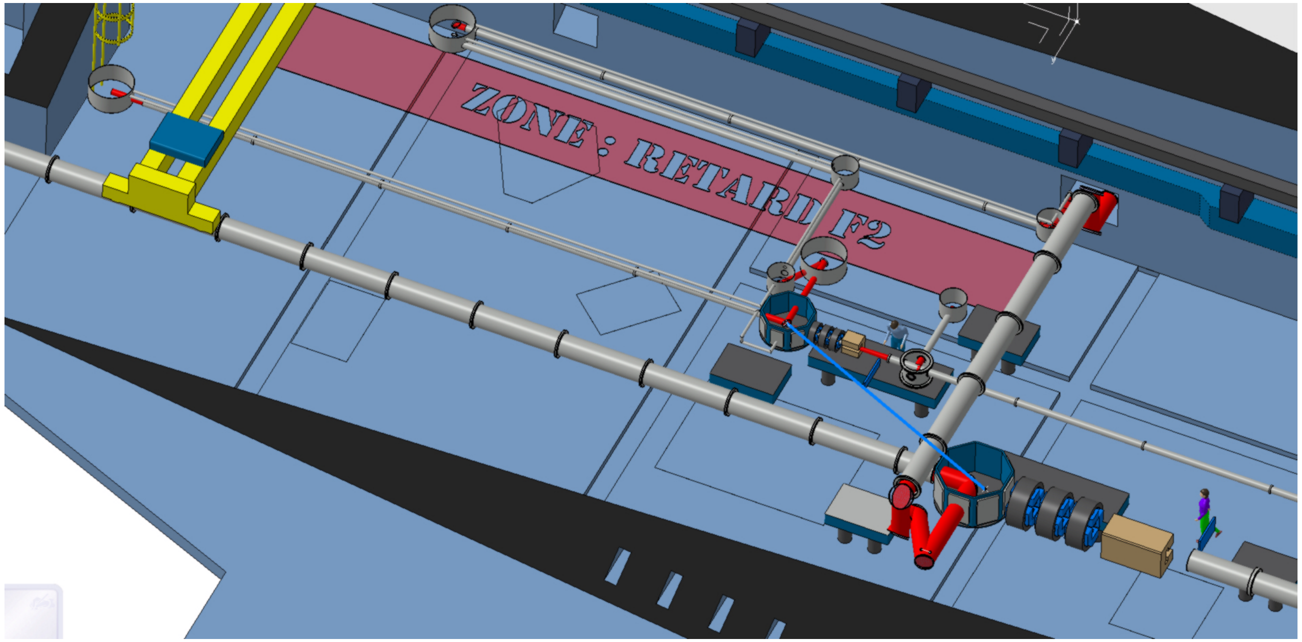
    with density gradient taylored, or high Z ionization
  - accelerator = F1 beam(15 J-75J, 15 fs – 1 ps, Ø=400 mm)
    gas cell, gas filled capillary (up to 1 meter!)

2017:all-optical multistage LWFA

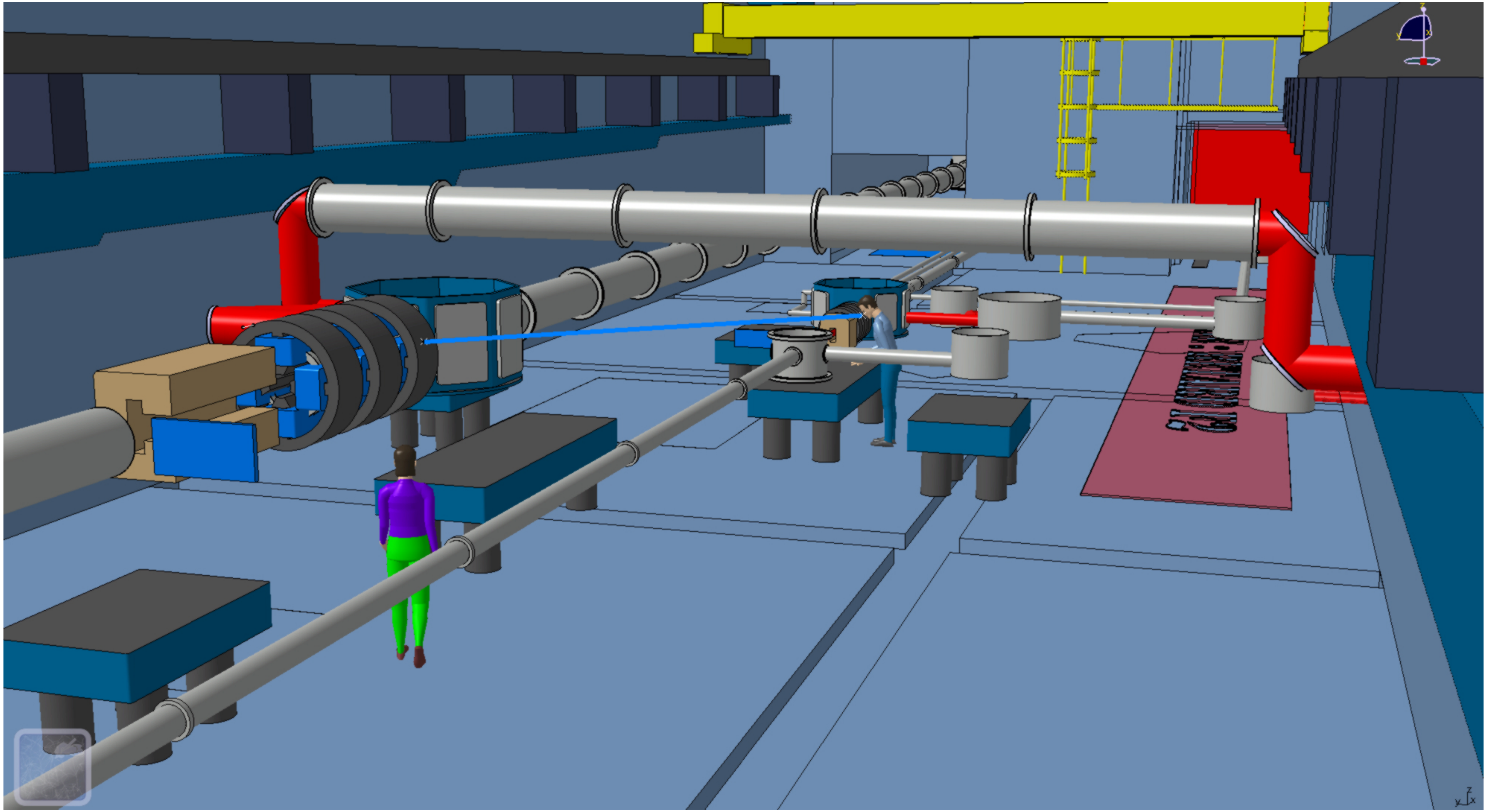


Exemple d'une expérience à 2 étages auprès d'APOLLON





Exemple d’une expérience à 2 étages auprès d’APOLLON



Conclusion

- CILEX puts a strong focus on laser particle acceleration and radiation generation - despite (temporary?) funding reductions
- CILEX lasers (APOLLON 10PW and satellite facilities) open field for dedicated LWFA experiments, wide range of driver param's (a0 , τ)
- Unprecedented, impressive challenges on instrumentation:
  - high intensity laser guiding over 1m x 200um (-> targetry)
  - compact, high quality, e– beam transport and max. non-destrucive diagnostics (accomodate betatron Xrays)
  - e– and laser beam alignment and synchronisation
- Fully instrumented experimental hall for e– and photon production will provide an advantage for programmatic and external users
- CILEX is looking forward to fruitful collaborations