Apollon multi-PW laser facility

Presentation and scientific program

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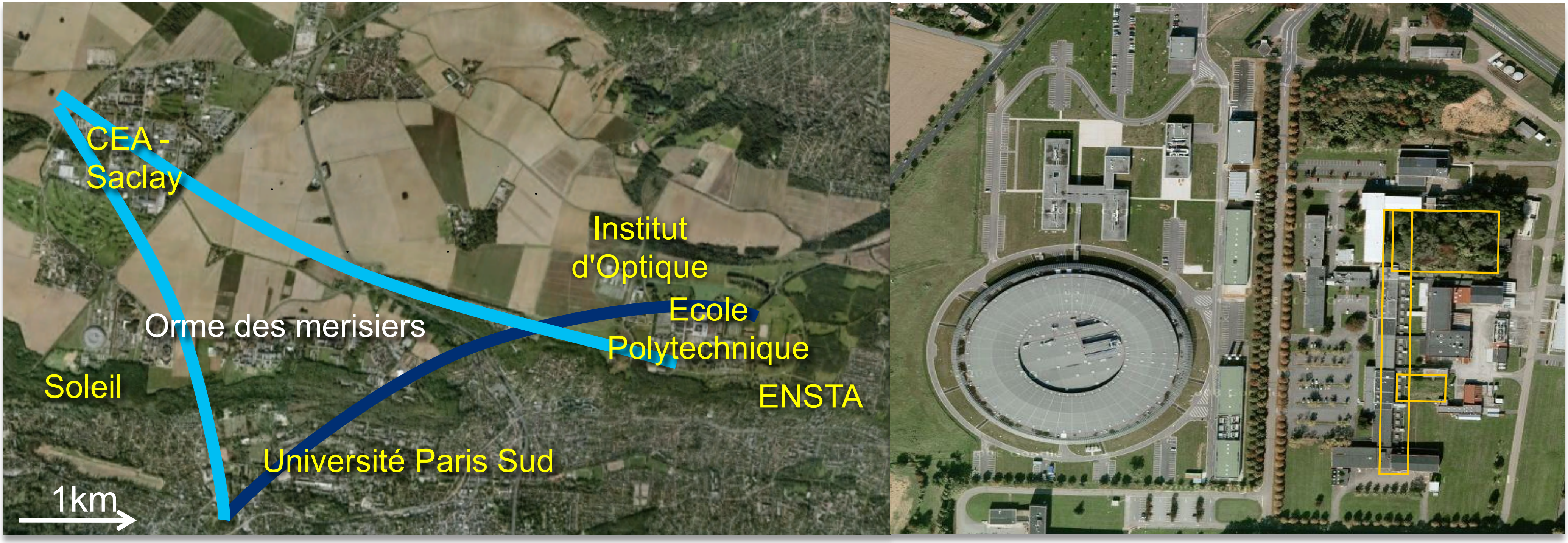
& CILEX – Apollon team

A project by laser, plasma, accelerator and high-energy scientists on Plateau de Saclay

Develop new instruments and an interdisciplinary centre to address physics at unexplored power densities



The project is hosted at l'Orme des Merisiers in former linear electron accelerator facility

Apollon: a combination of ultra-high intensities, few-cycle pulse duration, and multiple beams

High laser intensity

- $I > 10^{22} W/cm^2$ $a_0 = > 100$

Several complementary beams

- to perform pump probe experiments and multi-stage laser acceleration

High repetition rate

- To adjust laser and experiment parameters
- To have enough statistics

High contrast

- To be able to interact with solids without pre-formed plasmas

Reliability and stability

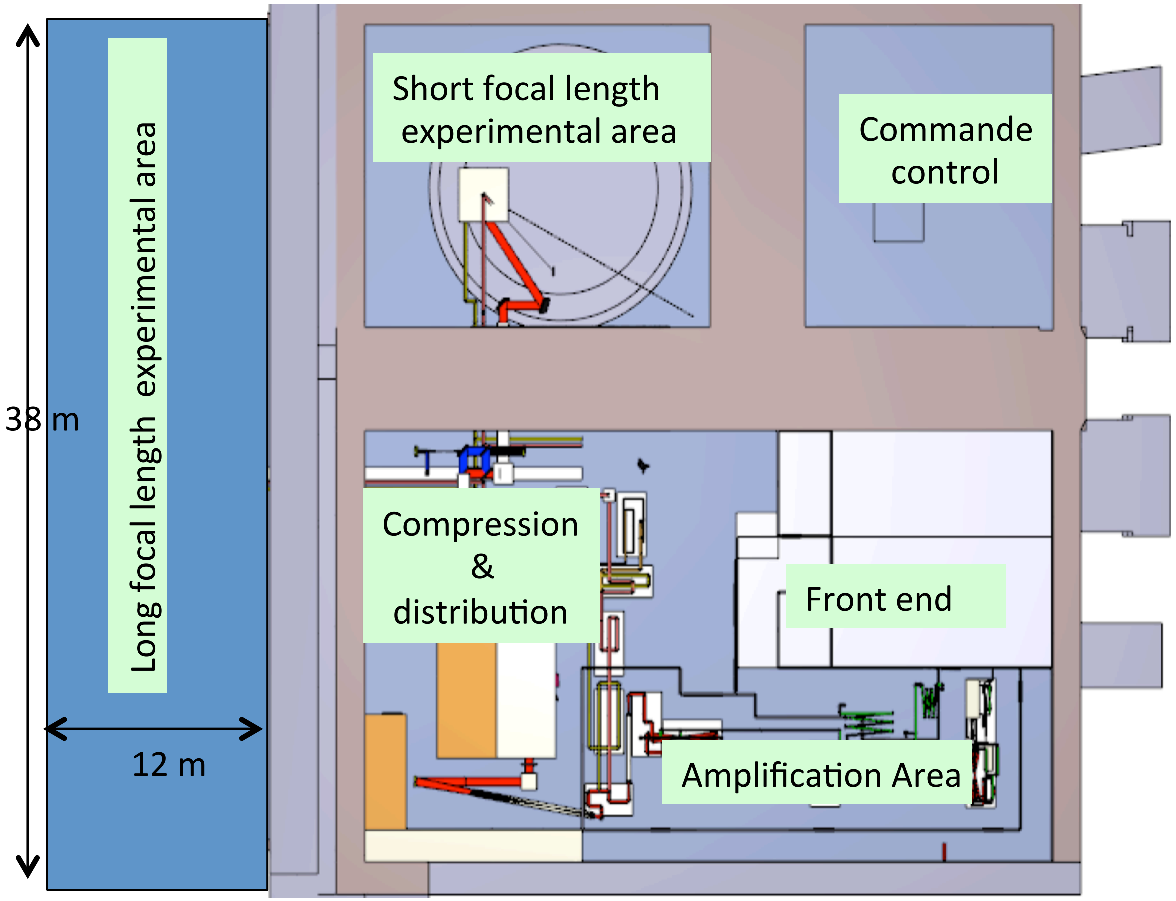
Good characterization of the beams

Dedicated experimental set up

Flexibility to make new experiments

Apollon : a multi-PW laser facility

4 synchronised beams and 2 experimental areas to address various scientific fields



4 PW beam: 15 fs / 60 J max

1 PW beam: 15 fs / 15 J max

Creation beam: 1 ns / 150 J max

Probe beam: 20 fs / 200 mJ

$I > 10^{22}$ W/cm^2 contrast > 10^{11} 1 shot / minute

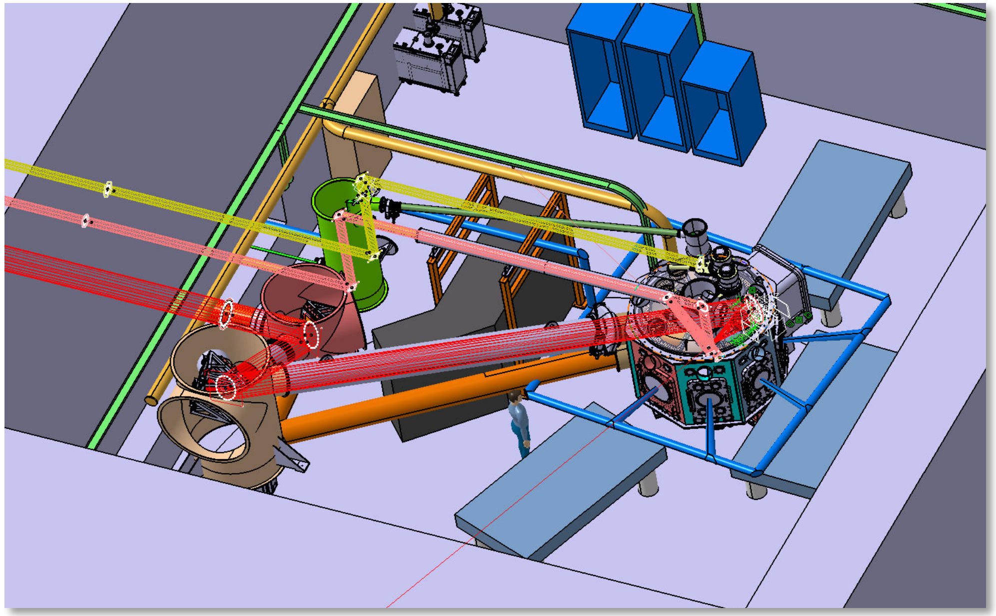
Total energy presently limited to 150 J possibility to increase up to 330 J

Apollon Status

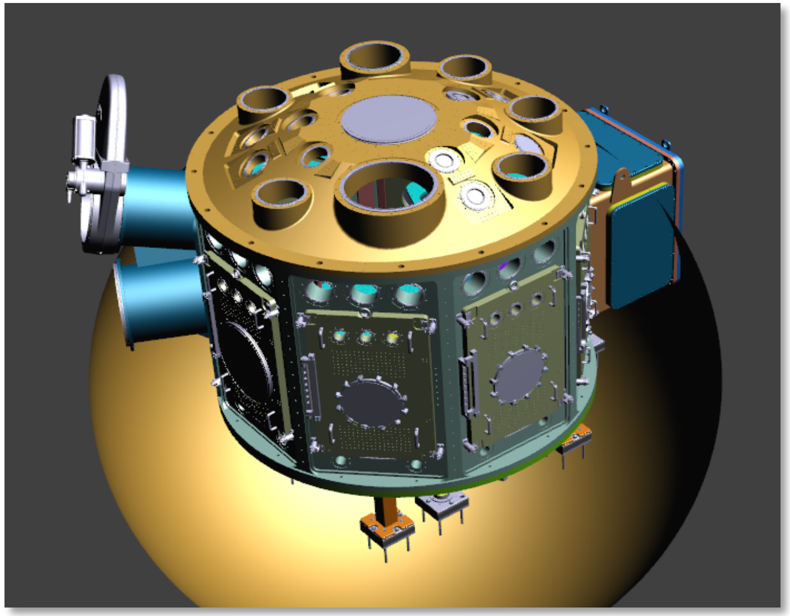
The building was delivered on March 2015
Compressor chamber is in place
The 3 first amplifier are in place
Expected 30 J compressed by the end of the year

Short-focal-length area

Versatile area and chamber adapted to various experiments



f/2.5 focussing → intensity > 10^{22}W/cm^2



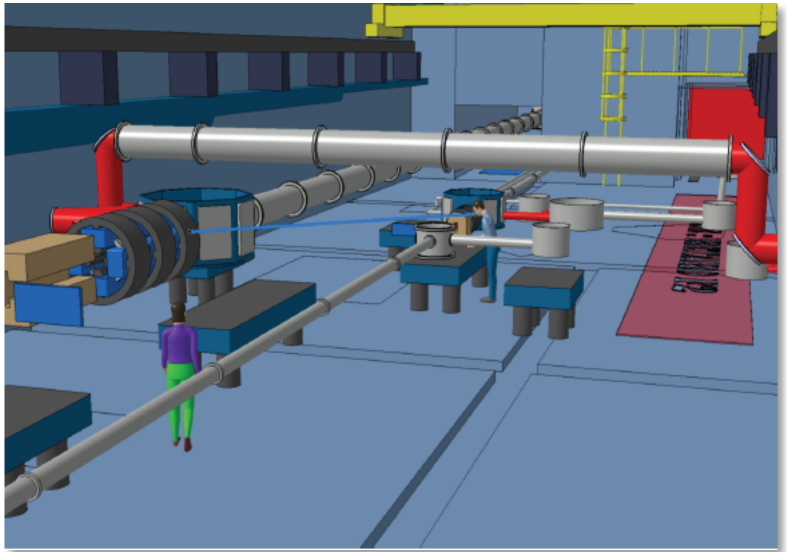
1 PW beam at ≈ any angle from 10 PW beam

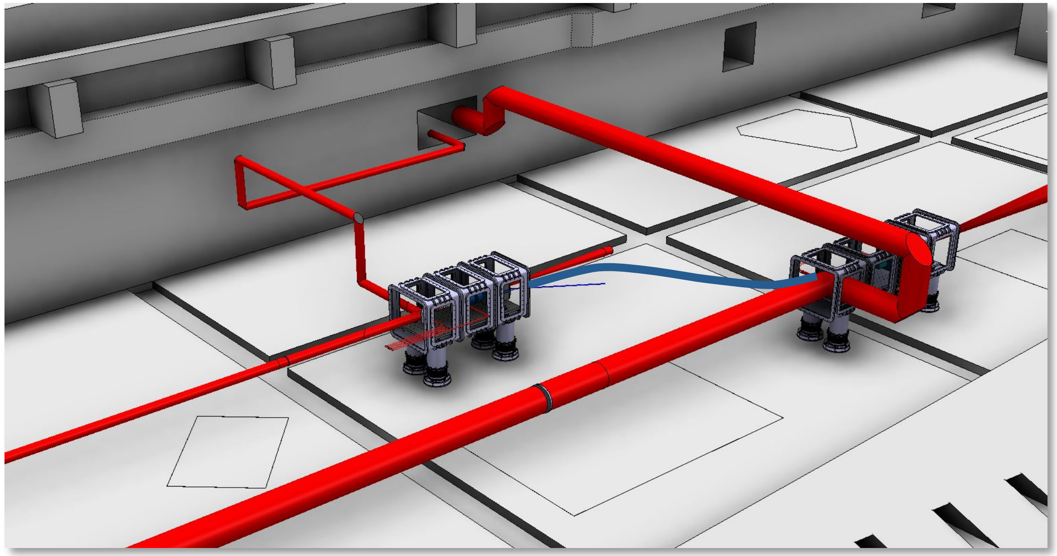
–> extreme (high energy, high dose, ultrashort, directional) beams of ions, X-rays and γ-rays

–> exploit the unique properties of the ion beam as a probe and for a variety of applications

Long focal-length area

Two chambers allowing 1 PW and 10 PW experiments and 2-stage schemes





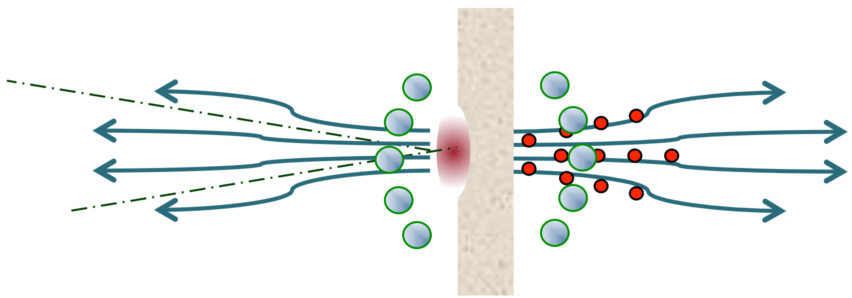
And very long focal lengths up to ≈ 30 m possible *e.g.* for electron acceleration

Apollon : in laser-matter interaction

Laser – matter interaction in ultra-relativistic regime

High energy absorption

leads to new particle acceleration and radiation mechanisms



electrons

protons, ions

neutrons

X, γ

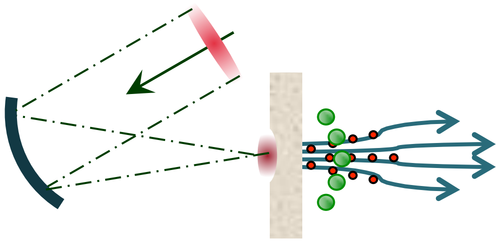
plasma heating

short and intense probe beams

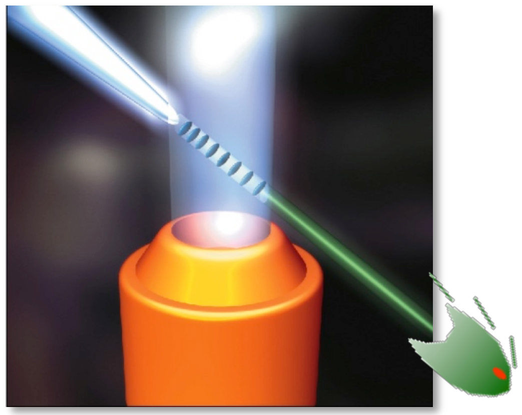
nuclear physics

high-field physics

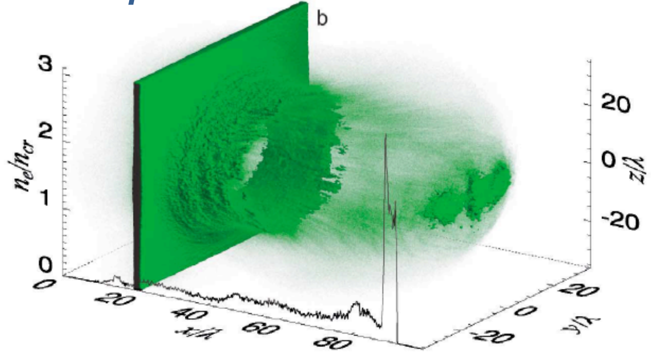
Apollon : a variety of scientific applications



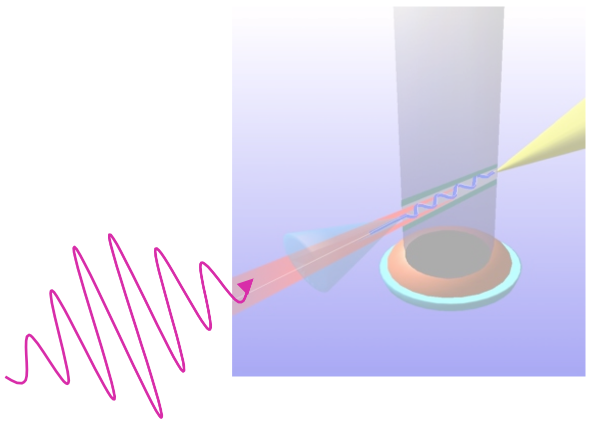
multi-GeV electrons



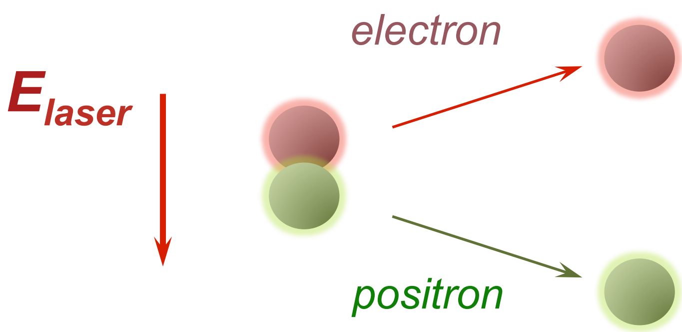
multi-GeV protons



X-ray , as sources, γ-rays

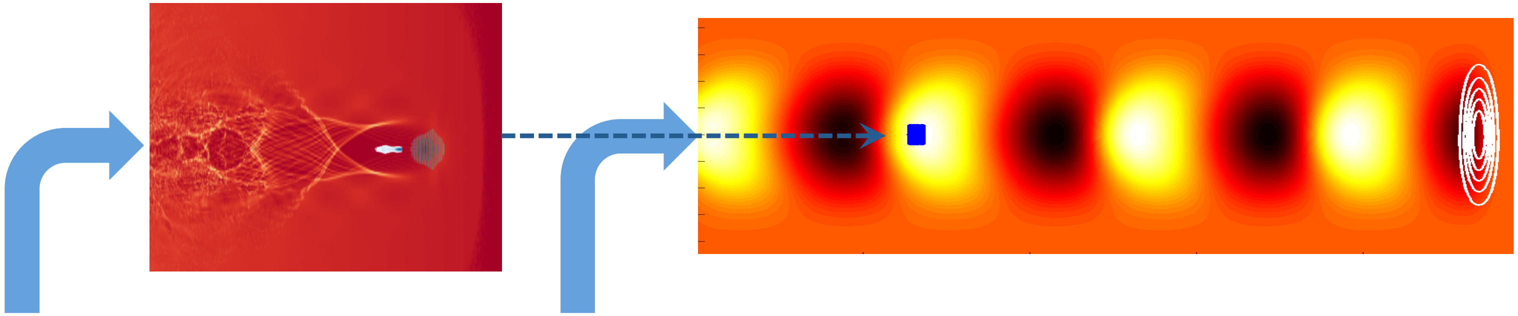


High-field physics



and applications ...

Electron acceleration



Motivations for laser-plasma acceleration

- Feasibility of a laser plasma accelerator scalable to high energies
  - high gradient technology and meter scale stages

- Test facility for multi-stage laser plasma acceleration

  & build a community of physicists

- Reliable relativistic electron source

  & build a community of users

- Study fundamental processes
  - Scaling laws for electron acceleration in UHI regimes

    Strongly to weakly nonlinear regimes, self-guiding, capillary guiding
  - Positron production and acceleration
  - Generation of radiation (betatron, undulator, Compton, Thomson)

B. Cros et al, NIMA **740** 27 (2014)

Toward a stable two-stage multi-GeV e⁻ beam

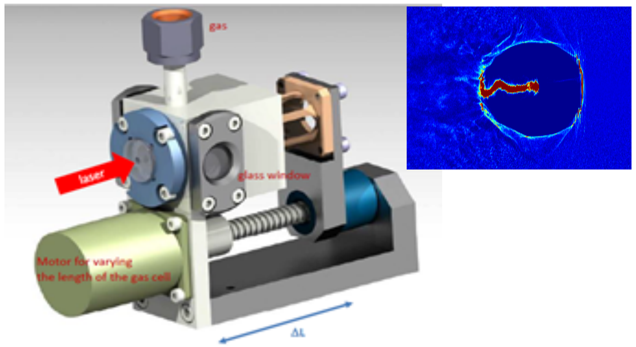
A two-stage approach on the way to a high-energy all-optical electron accelerator

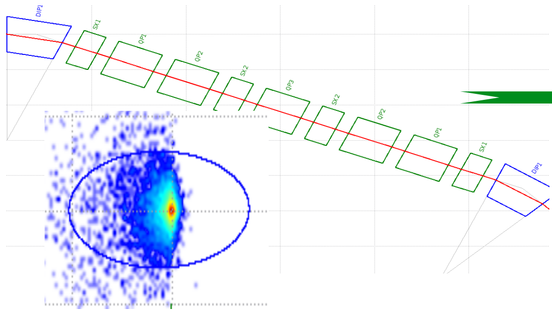
Special attention on stability, reproducibility, and quality of the e⁻ beam

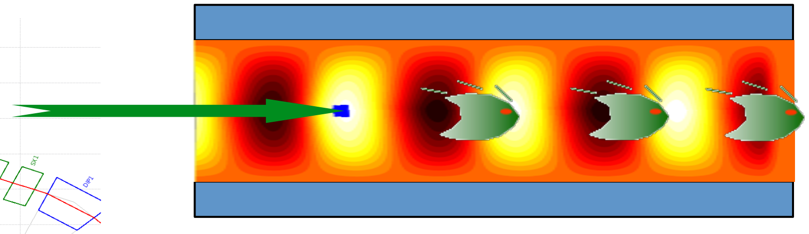
all-optical source

transport

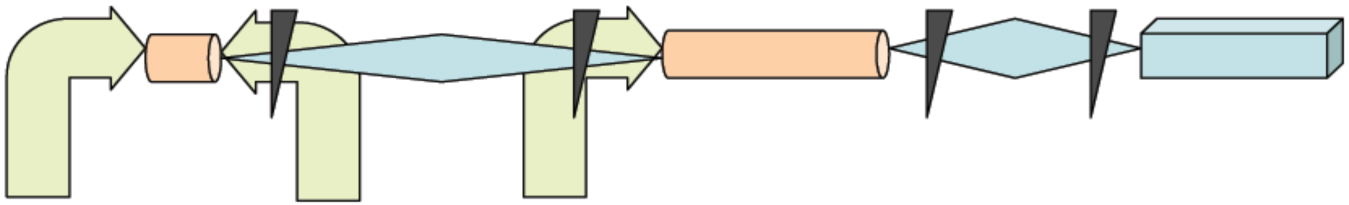
acceleration to multi-GeV







electron source transport acceleration diagnostics beam dump



Work is planned in 3 phases

- **PHASE 1**: 2013-2017

  Design experiments in Long Focal-length Area (LFA)
  - Research program on other facilities
  - Conceptual & technical design of the experimental set-up
  - Procurement & implementation of equipment in LFA

- **PHASE 2**: 2017-2018

  Commissioning of the 1 PW beam and facility through experiments in the bubble regime
  - Validation of laser specification ($I \approx 10^{20}$ W/cm^2, $a_0 \approx 7$)
  - Comparison to scaling laws and exploratory experiments
  - Injector optimization

- **PHASE 3**: 2019 –

  Develop a two stage Laser Plasma Accelerator (injector/accelerator)

  e^- beam transport, focusing, synchronisation and injection into a plasma wave over long distance

Ion acceleration

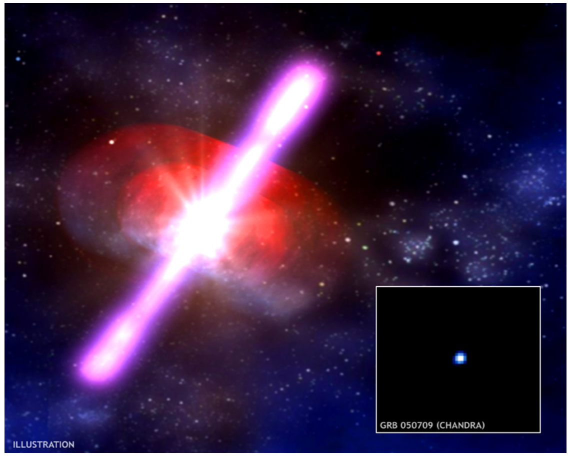
Ion acceleration: a broadband scientific program

- A clean (high contrast, tight focus) multi-PW laser system will allow:
    - to push proton energies to the GeV level
    - to explore "exotic" acceleration mechanisms
        - direct acceleration of thin (sub-μm) targets by strong radiation pressure
        - directional Coulomb explosion of ultra-thin (nanoscale) targets
    - to enter new regimes where both electrons and ions are relativistic

- A highly reproducible and controllable proton beam (>10^{13} p) of several hundreds of MeV will have numerous applications such as:
    - radiography of dense objects with ps resolution
    - material science (time-dependent radiation induced defects)
    - warm dense matter physics
    - relativistic laboratory astrophysics
    - high-energy nuclear physics (including neutron production)

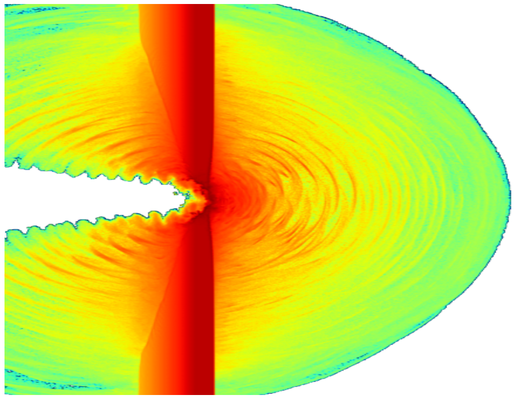
Ion acceleration: a broadband scientific program

Development of a work station dedicated to ion studies
for fundamental studies and applications



Clear signatures of the transition
to the ultra-relativistic regime

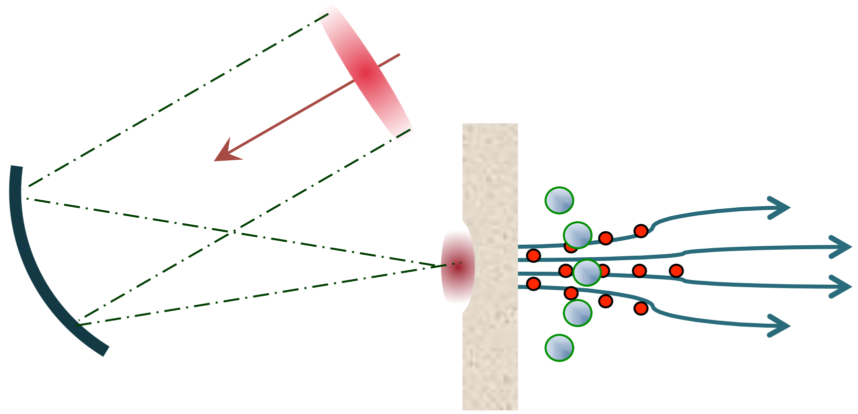
PIC simulations in the APOLLON parameter range



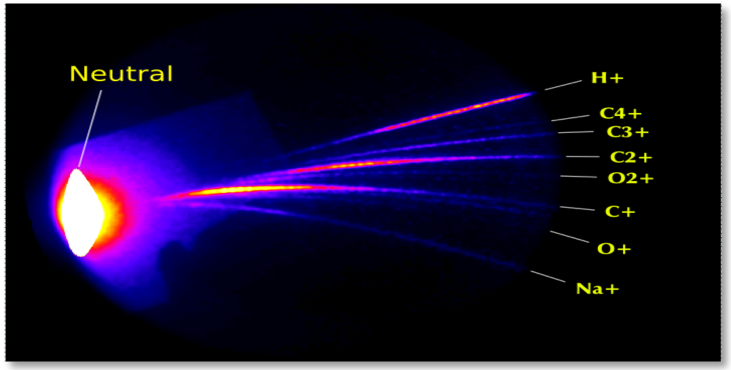
Fundamental studies : TNSA to RPA
Benchmark for laser commissioning

Toward GeV proton beams

Today: small fraction of ions are accelerated

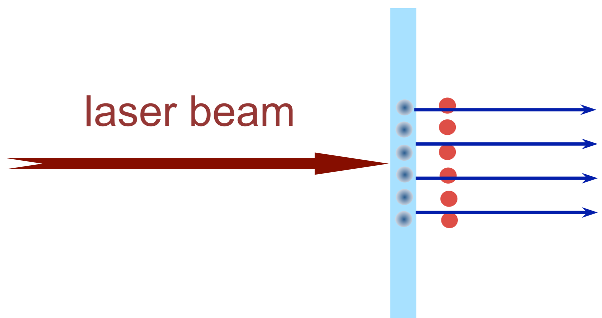


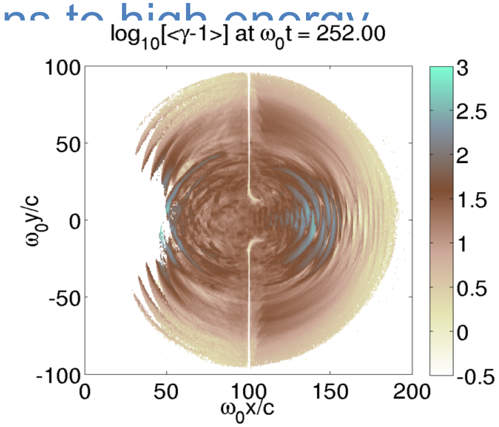
State of the art : protons <100 MeV



Tomorrow : expulsion of all electrons inside the focal spot

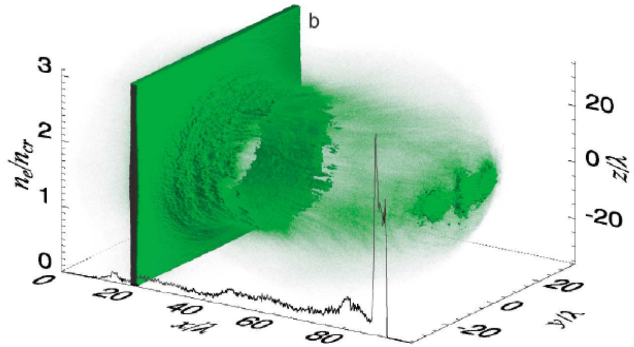
acceleration of all ions to high energy





1.8×10^{22} W/cm^2, 100 nm, GeV p

multi-GeV protons at I >10^{23}W/cm^2



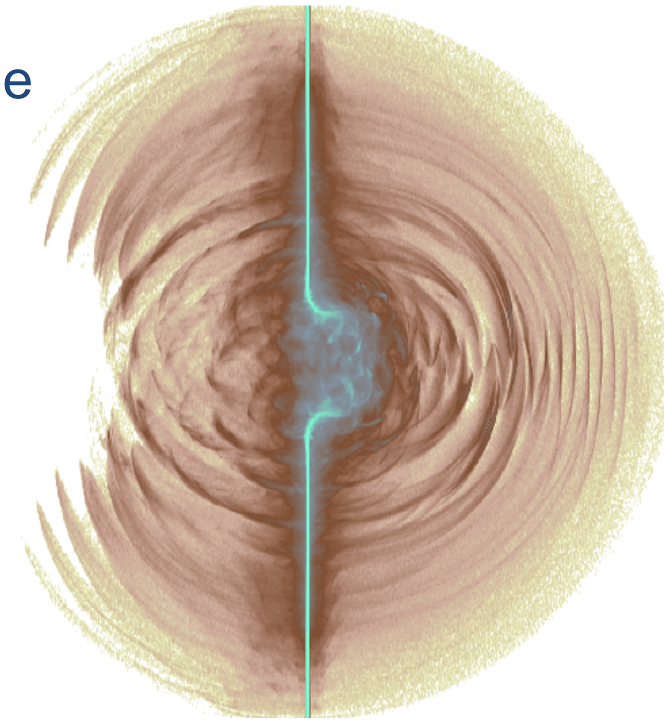
T. Esirkepov et al.

Basic studies at ≈ 10^{22}W/cm^2

~10^{19}	~10^{21}	~2 10^{22}	~2 10^{23}
~5 MeV	~60 MeV	~250 MeV	~GeV

Transition toward a radiation-pressure regime where the ion bunch is:

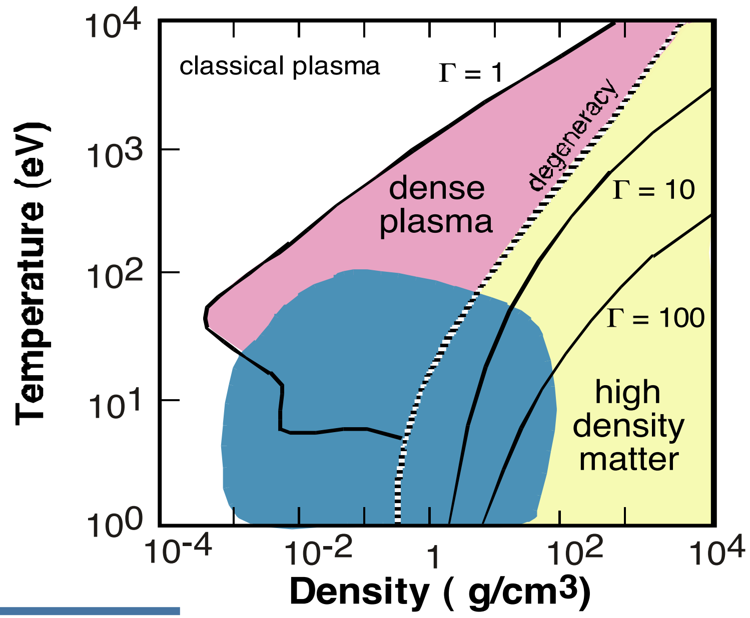
- collimated
- "monoenergetic"
- efficient



Effect of laser contrast and polarization

Effect of radiation friction

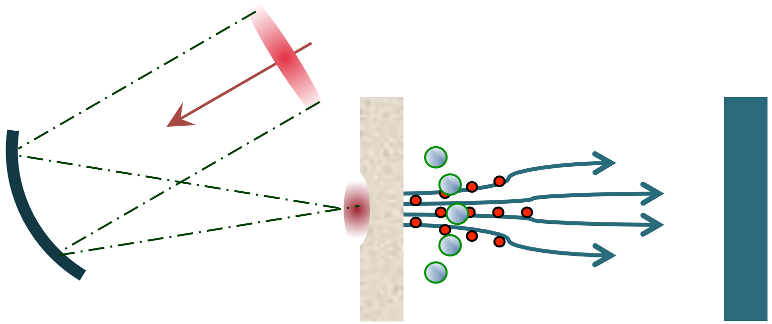
Application to warm dense matter



Warm dense matter

planetary interiors, cool dense stars, ICF implosions

Heating of a second target by the ion beam



Currently: ion heating up to 15 eV

With 150 J of Apollon, high temperatures can be realized

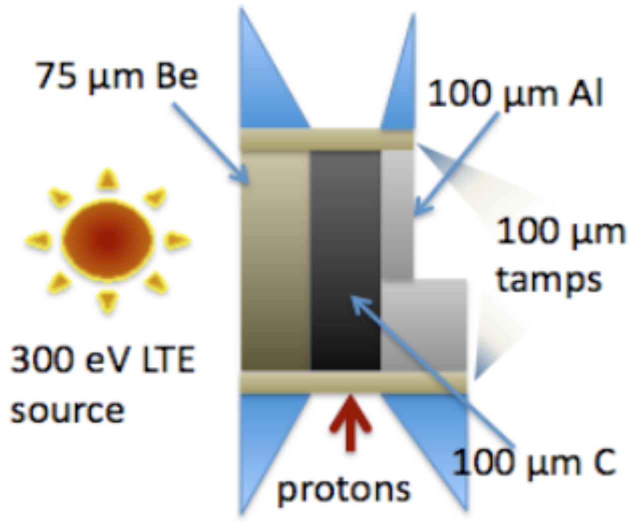
Most importantly with the multi-beam system available

simultaneous probing with protons and/or x-rays

Application to inertial confinement

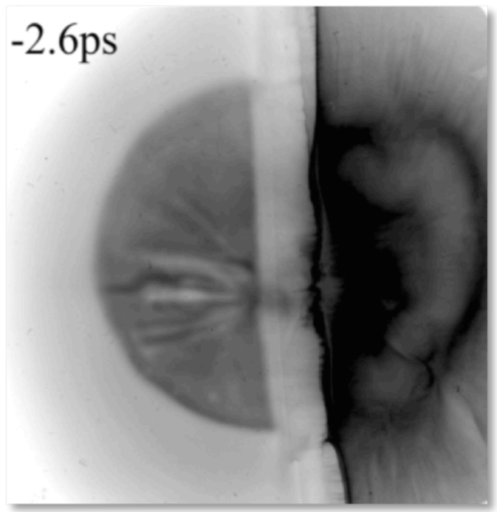
Alpha particle stopping in hot dense D-T plasma

- Exploits the multi-beam capability of Apollon
- Proton stopping in heated hydrogen gas as already demonstrated at the multi-beam ELFIE laser syster



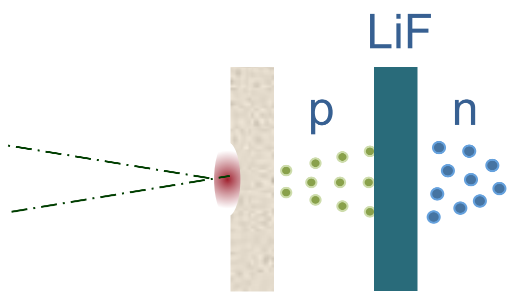
Proton Fast Ignition studies

- To probe dense objects and strong fields, higher energy ion beams, and in larger number @ Apollon
- Study transport in warm dense plasma at much higher temperatures

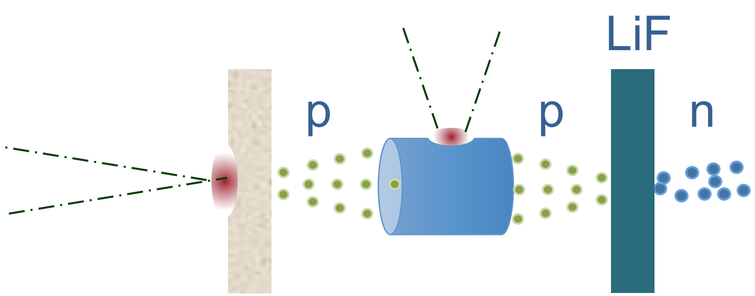


Sub-ns neutron sources

Production of neutrons using laser-generated protons p + $^{7}Li \rightarrow {}^{7}Be$ + n



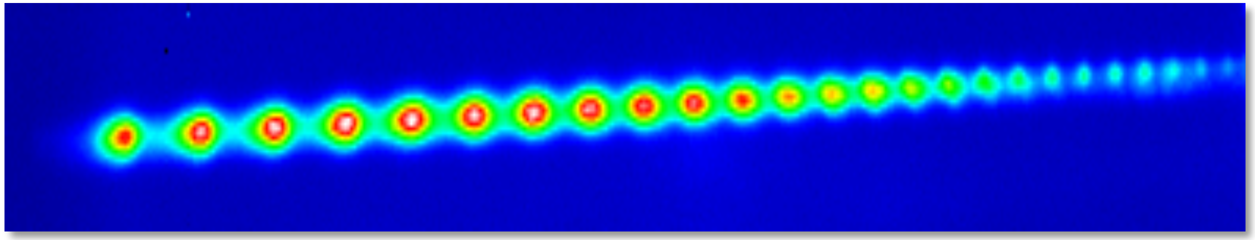
neutrons up to several 10 MeV



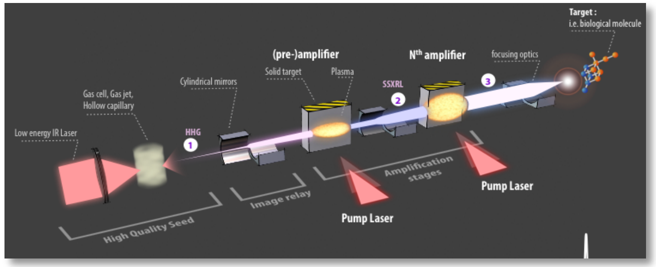
small source-size neutron beam
using a laser-generated lens

D. Higginson et al., PRL 2015

X-rays, γ-rays, *as* sources

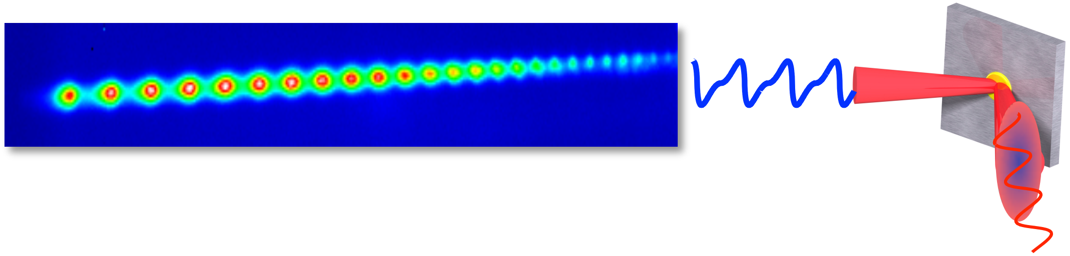


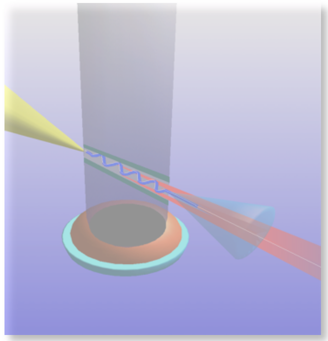
Many schemes for x and γ all-optical sources



x-ray laser

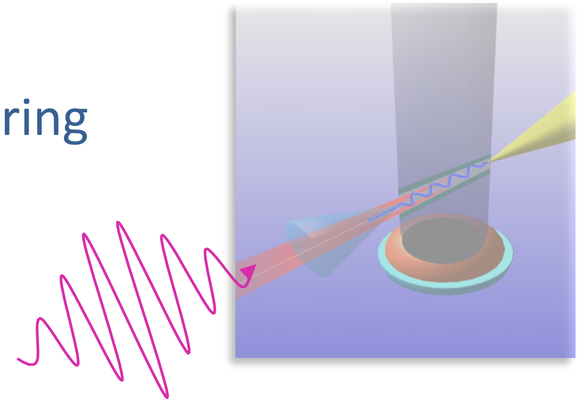
high-order harmonics

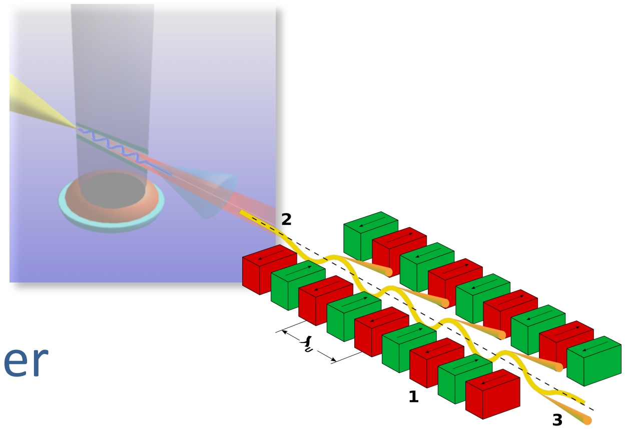




betatron emission

Compton scattering





free electron laser

X-rays: a broadband scientific program

The activities proposed on APOLLON aim at:

extending the capabilities of the laser-induced radiation sources
$h\nu \approx$ 30 eV to tens of keV
energy ≈ a few nJ to a few mJ
duration ≈a few tens of attoseconds to 10 nanoseconds

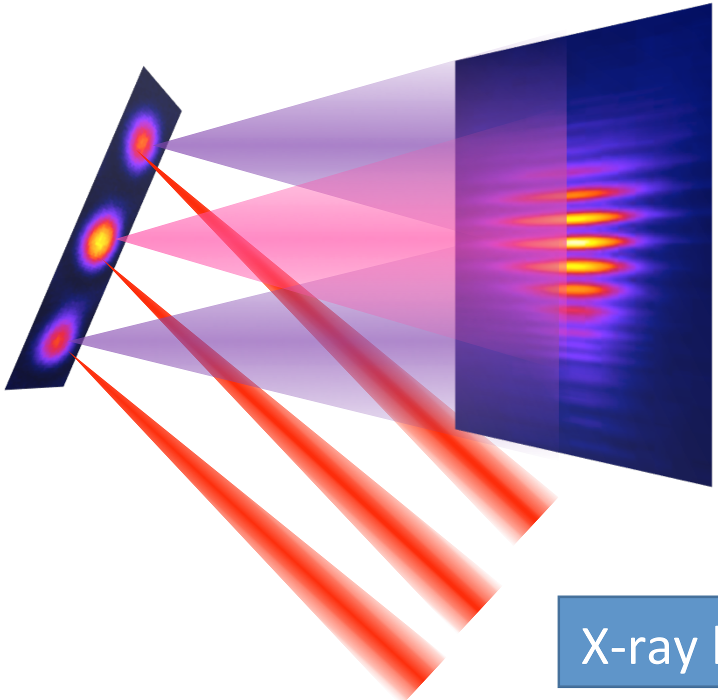
Various approaches will be followed:

plasma mirrors: high-order harmonics emission from solids

x-ray lasers: reaching shorter wavelengths and higher intensities
new schemes such as inner-shell photo-pumping
breaking the ps duration barrier, etc

betatron radiation
and possibly flying mirrors

X-ray sources: a broadband scientific program

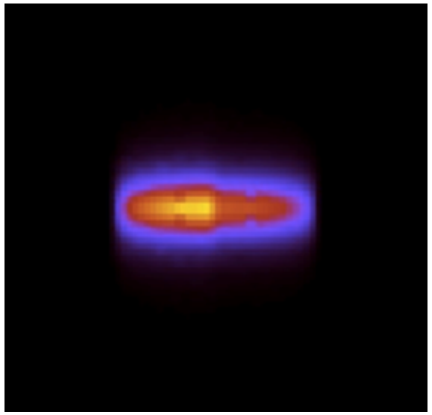


Relativistic Optics with mirrors

Control of the laser parameters :
Intensity, Contrast and spatio-temporal couplings

Light manipulation with Plasma
Ultra-High XUV intensities
Route to atto-physics...

X-ray lasers, betatron studies and applications



X-ray laser future trends :
shorter wavelengths, brighter beams, shorter durations!

Betatron : produce a unique source
(500 keV collimated , 10^{10} ph/shot) for applications
in bio-molecule imagery

First harmonic experiments on Apollon

Focus the beam at the highest possible intensity on a solid target
and measure the harmonic spectrum

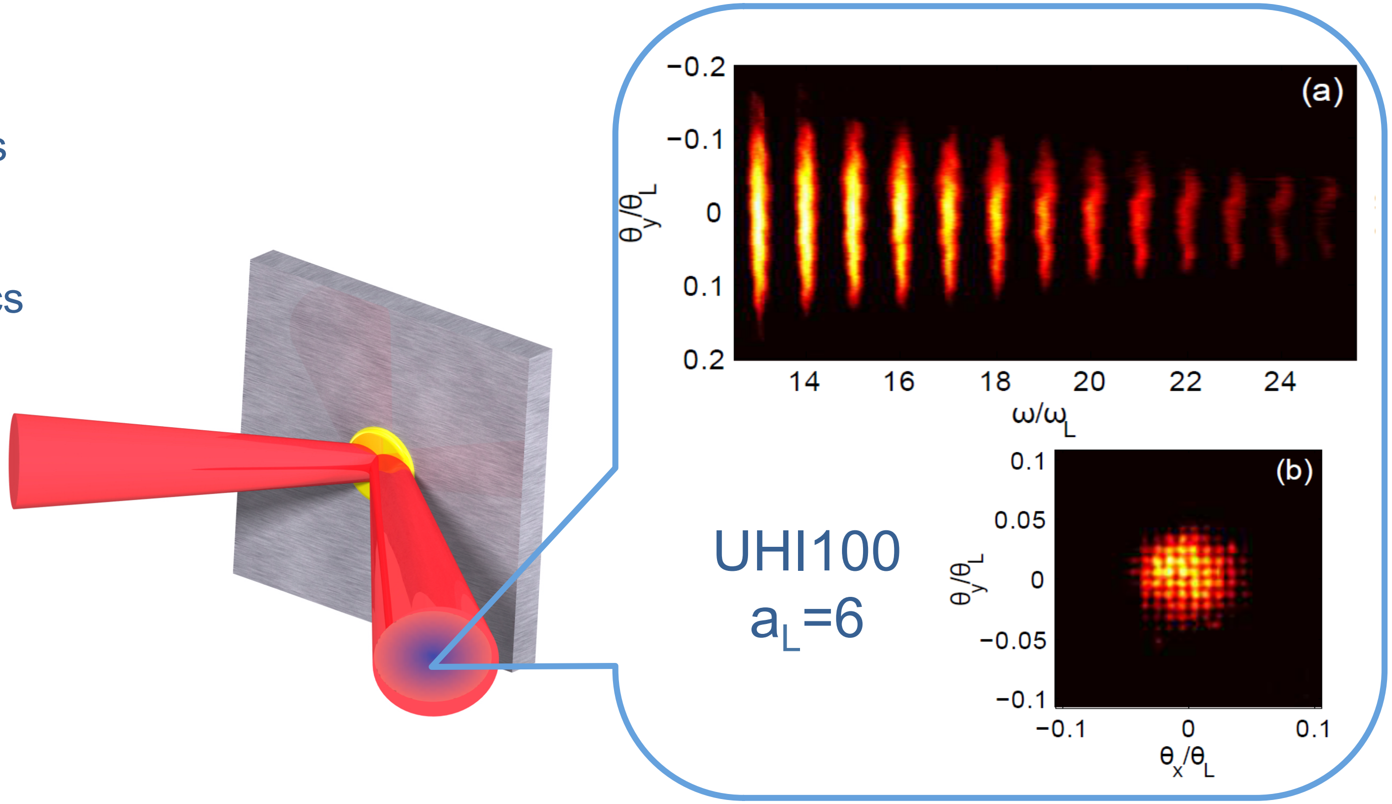
and gradually increase the complexity of experiments…

Metrology

- spectral diagnostics
- spatial diagnostics
- energy diagnostics
- temporal diagnostics

Target

- target density
- density gradient
- target geometry
- target diagnostics



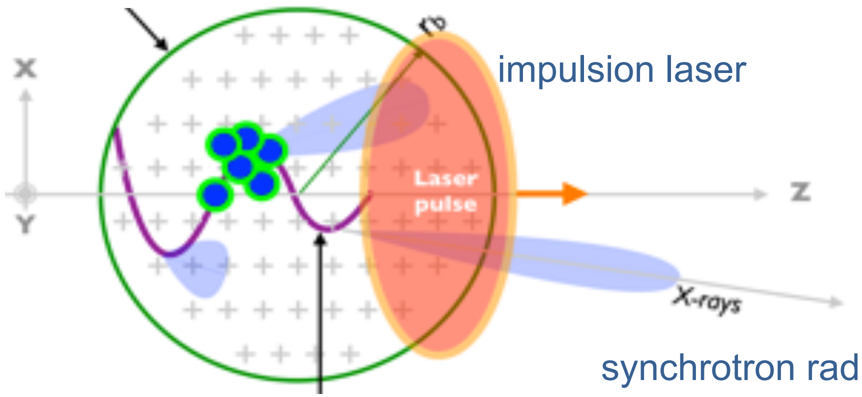
Betatron radiation up to MeV

Electrons oscillate radially in the bubble during acceleration …

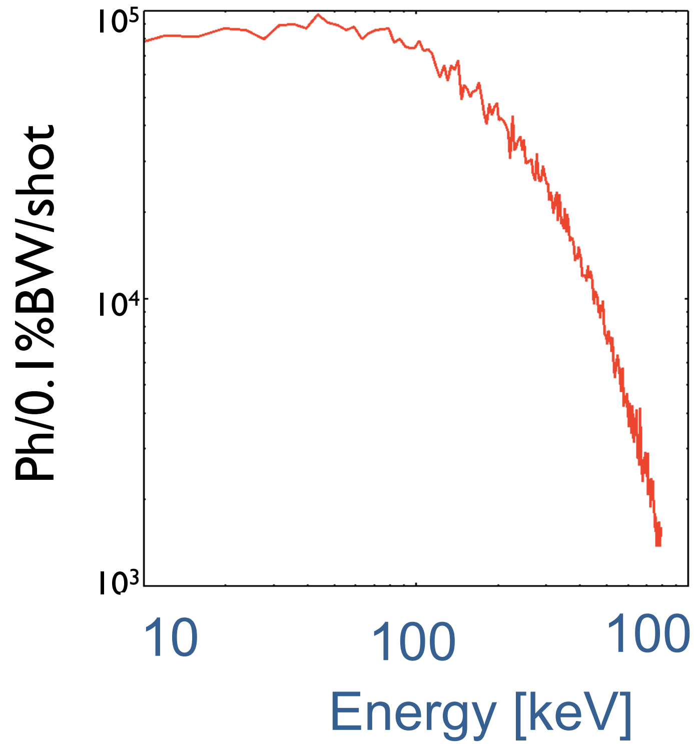
… and emit x-rays

100s keV with PW laser (GeV e⁻)

ion cavity



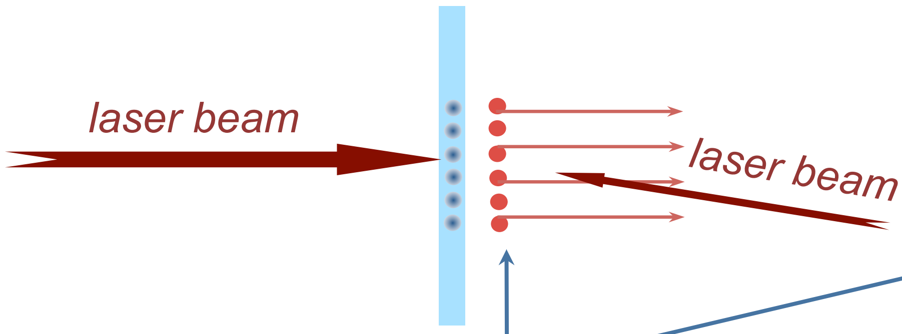
betatron orbit

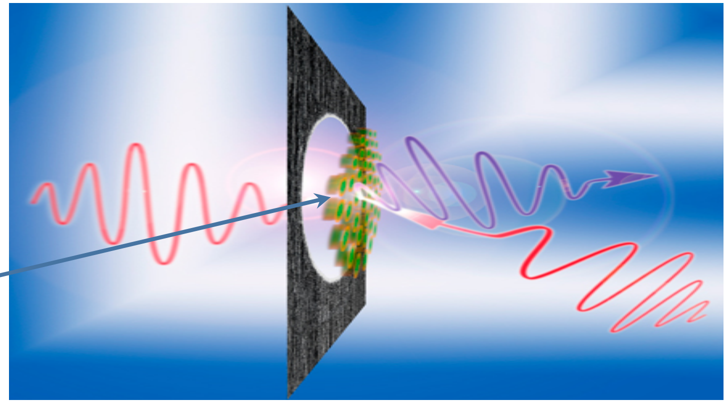


A. Rousse (2004), S. Corde, K. Ta Phuoc et al., Rev. Modern Phys. **85**, 1 (2013)

Relativistic flying mirror

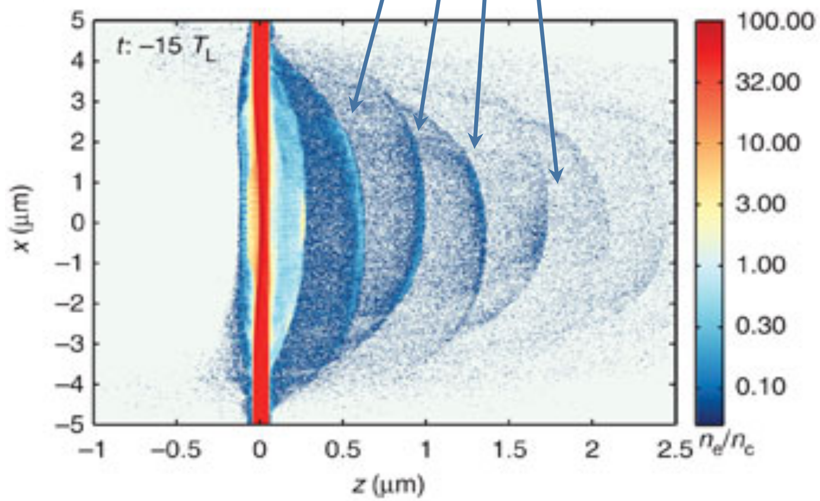
Toward short-wavelength compressed and focussed x-ray beams

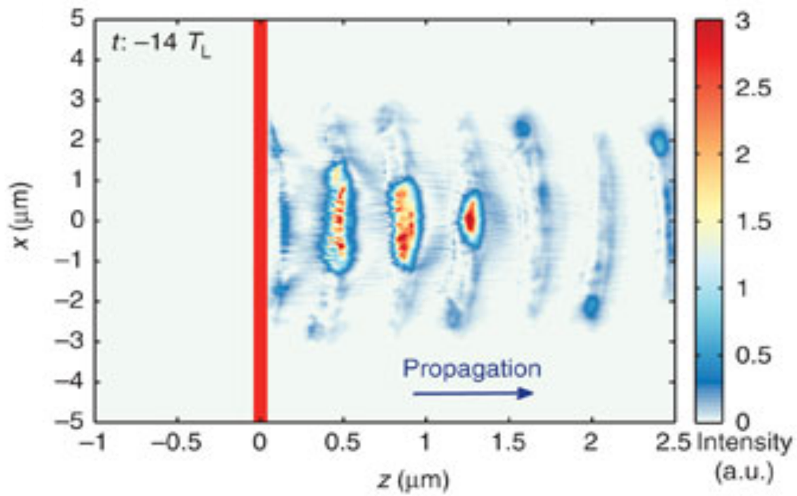




electron flying walls

ultrashort high-frequency photon bunches





First demonstration - D. Kiefer et al., Nature comm. 2013

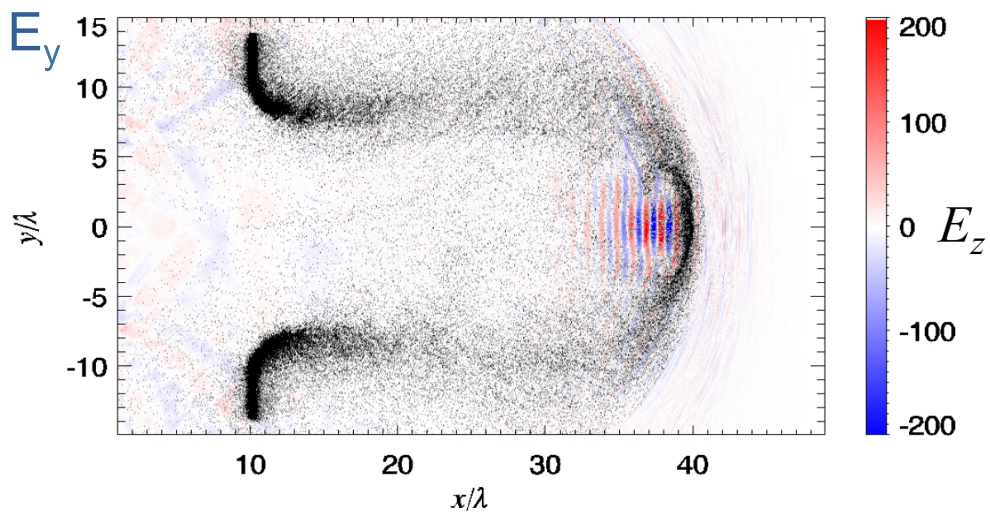
Flying mirrors with thin foils

Esirkepov et al, PRL. 103, 025002 (2009)

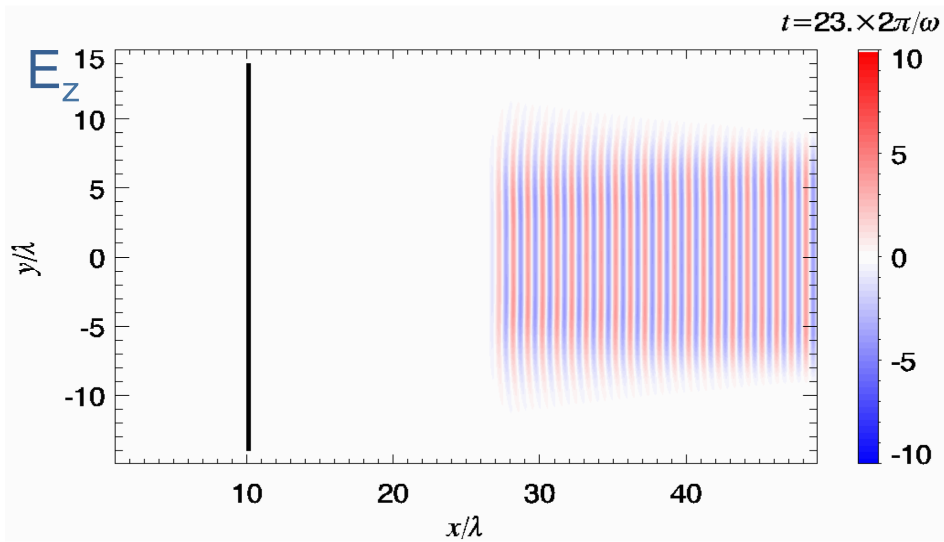
$t = 77\times 2\pi/\omega$

Driver

a=300   I=1.2×10^{23} W/cm^2



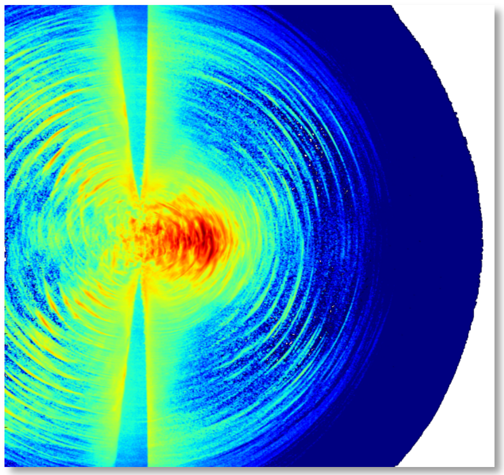
Driver



Apollon
2nd intense beam!

I=1.2×10^{19} W/cm^2

High-field physics



Apollon and high-field physics

New possibility to access extreme regimes of interaction

Effective strength of the electromagnetic fields exceeds the critical fields of QED

New effects are predicted to occur by quantum electrodynamics

which can be tested in such extreme conditions, e.g.:

- electron dynamics strongly dominated by radiation-reaction and quantum effects
- multiple photon emission occurs in the full quantum regime

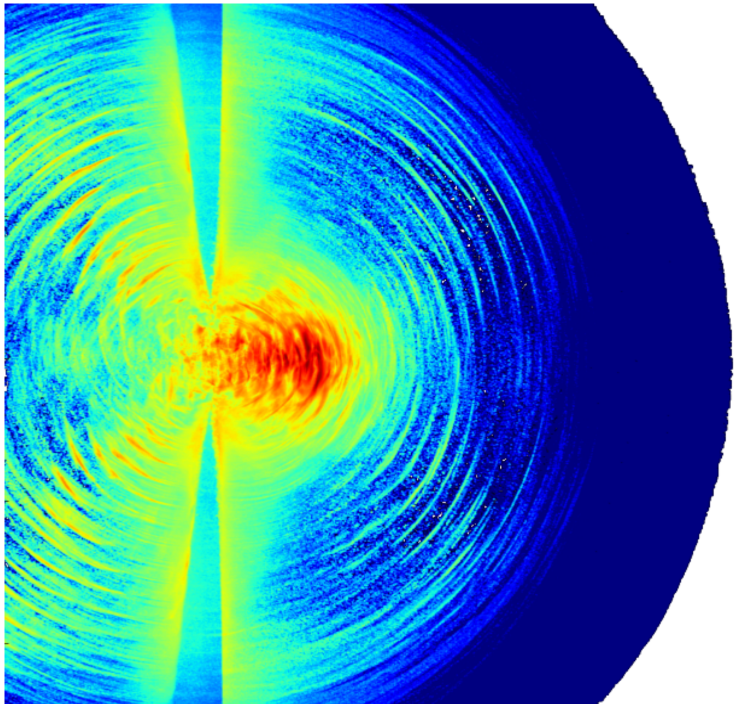
Apollon will allow help understanding fundamental problems in CED and QED

High-field physics and Apollon

Fundamental importance to account for physical effects occurring above 10^{22} W/cm^2 as Radiation Reaction forces

Fundamental difficulties to describe properly Radiation Reaction forces in CED and QED

Needs for theory and intensive PIC-Monte Carlo simulations

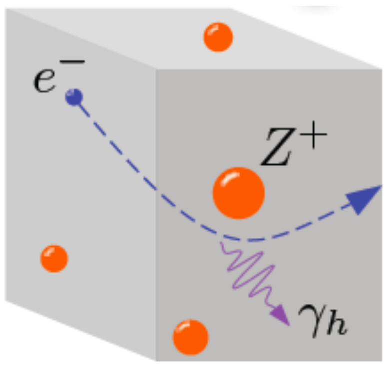


Radiation Reaction effects in plasmas
and new developments in intensive PIC simulations

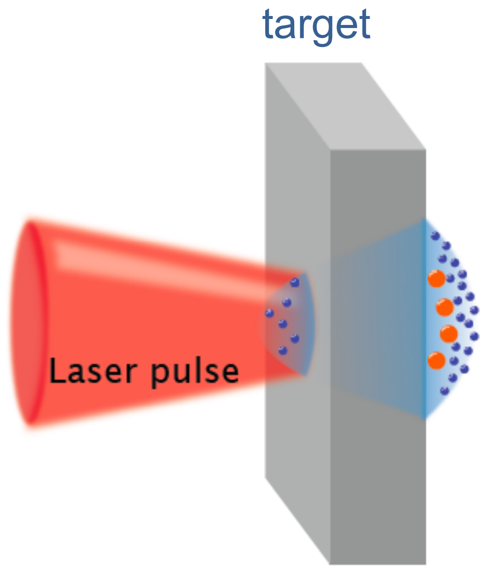
Classical and Quantum Radiation Reaction descriptions and non-linear Compton scattering with APOLLON

New mechanisms at extreme light intensities

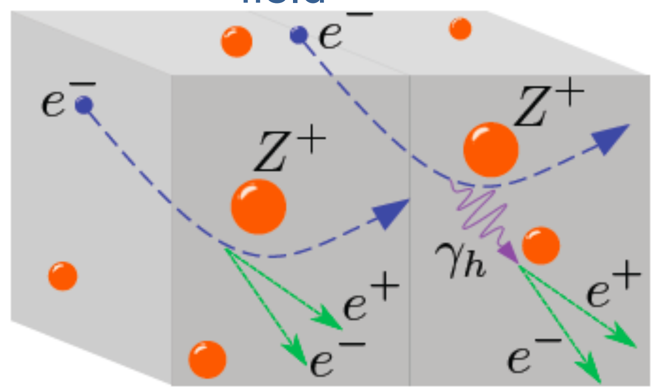
Bremsstrahlung



generation of high-energy photons

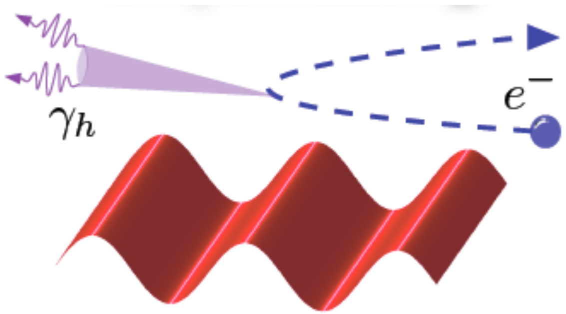


pair production in strong Coulomb field



production of e^-e^+ pairs through e^- or high-energy photon

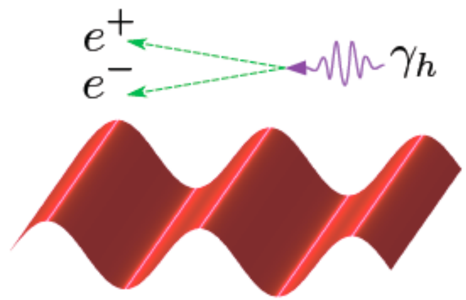
nonlinear Thomson & Compton scattering



$$e^- + n\,\gamma_L \rightarrow e^- + \gamma_h$$

generation of high-energy photons

pair production from laser field – Breit-Wheeler



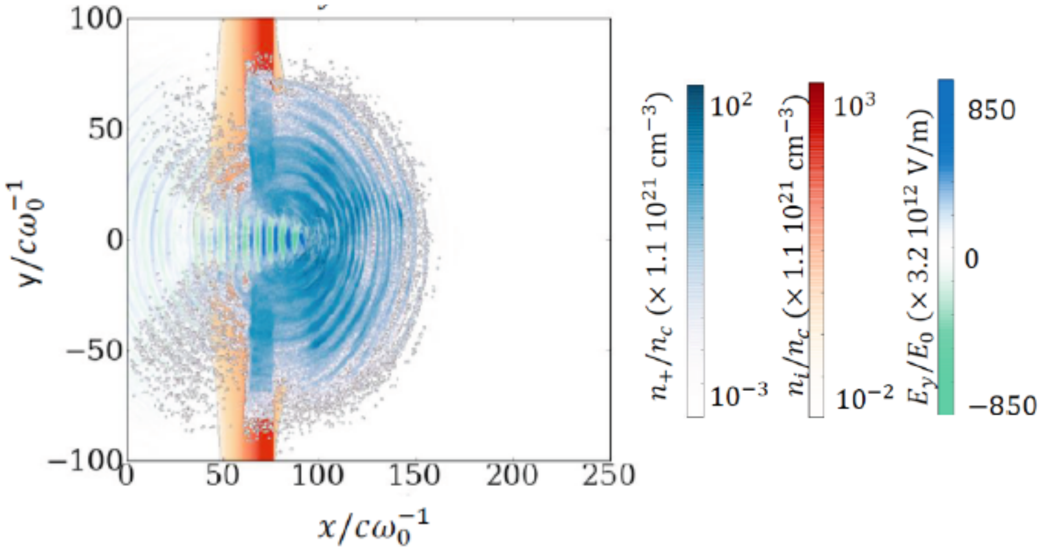
$$\gamma_h + n\,\gamma_L \rightarrow e^- + e^+$$

high-energy photons + laser

Electron – positron pair production

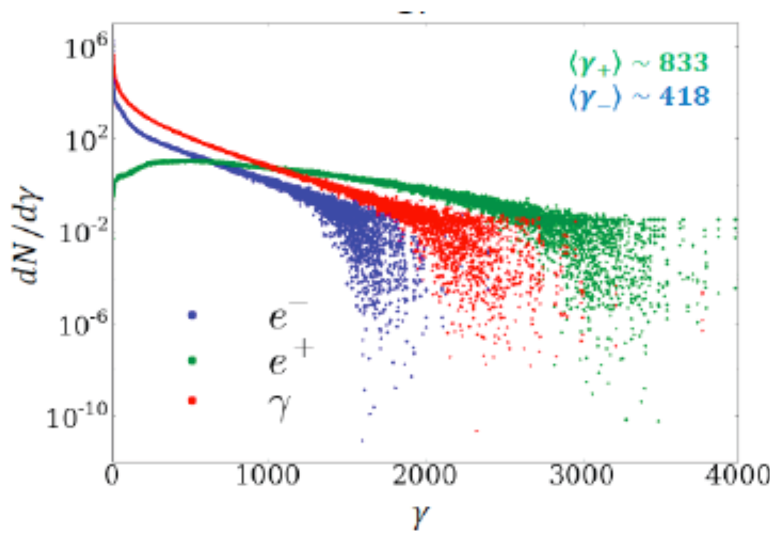
Several mechanisms can produce electron – positron pairs

E_y field and positron & ion profiles



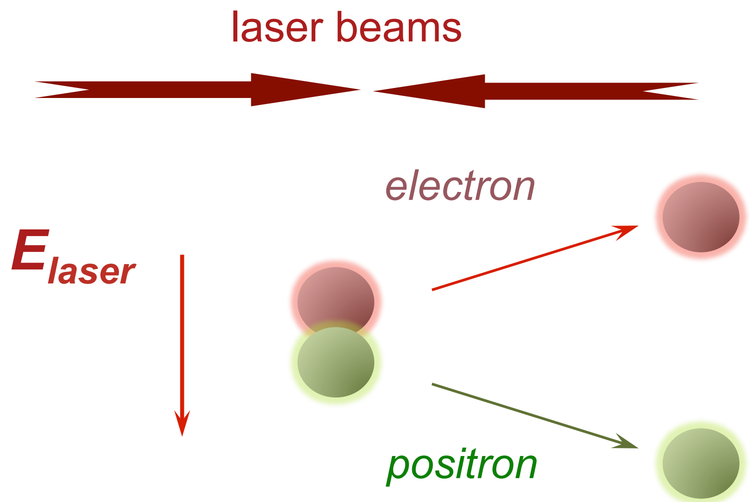
≈ 10 n_c at 10^{24} W/cm^2

particle energy distribution



An example of high-field physics

The laser electric fields separate virtual e⁻ & e⁺ before they annihilate



Separate the 2 particles by λ_C during their lifetime

or give each particle an energy mc^2

$E_{Schwinger} = 1.3\ 10^{18}$ V/m

$\tau \approx \hbar/mc^2 = 1.3\ 10^{-21}$ s $\quad \lambda_c = \hbar/mc = 3.9\ 10^{-13}$ m

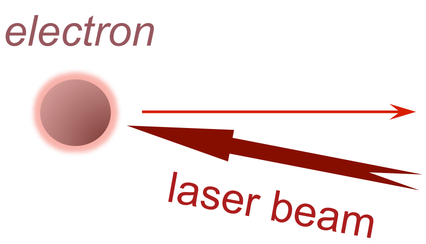
$eE\lambda_c > 2mc^2 \quad I > 2.3\ 10^{29}$ W/cm²

But, even at lower intensities, photons interact with virtual particles

QED effects are "easily" reached !

The electric field in the electron frame can "easily" reach the Schwinger field

$E_{rf} = \gamma E\,(1-\beta\cos\theta)$ $\qquad E_{rf}\ \alpha\ \gamma I^{1/2}$ $\qquad I \;\text{–>}\; I_{rf} = \gamma^2 I$



with $I = 2.3\ 10^{22}$ W/cm^2 $\quad \gamma = 1500$ [750 MeV] –> $E_{rf} = E_{Schwinger}$

On Apollon, few 100 MeV electrons will be enough

Operation of the Apollon Facility

- Facility will be opened to national and international scientists
  - The experimental programs on APOLLON will be decided, on an annual basis, by the Steering Committee, taking into account suggestions from an independent Program Committee.
- Beam time allocation per year
  - The goal is 140 days for users divide in 20 campaigns
  - Maintenance and configuration changes 60 days
  - Laser development 50 days
- Experiments
  - Each experimental area will perform one after the other.
  - Experimental campaigns will be defined on 4 weeks basis
  - The laser will deliver pulse sequences on demand for users 5 hours per day.
  - At the beginning, 2 days will be used for changing configuration between experimental areas
- The experiment should use as much as possible every laser shots

Conclusions

- High energy and intensity laser sources can explore fundamental physics research
- Need versatile and reliable laser facilities

- Qualification and first experiments of multi-PW Apollon facility expected end of 2016, beginning 2017

- Open in 2018

Apollon

CileX

INSTITUT d'OPTIQUE GRADUATE SCHOOL

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ISMO

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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& collaborators

INVESTISSEMENTS D'AVENIR

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