Apollon multi-PW laser facility

Presentation and scientific program

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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
High laser intensity
• $I > 10^{22} \text{W/cm}^2$  \(a_0 = > 100\)

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
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 \( \rightarrow \) intensity \( > 10^{22} \text{W/cm}^2 \)

1 PW beam at \( \approx \) any angle from 10 PW beam

\( \rightarrow \) extreme (high energy, high dose, ultrashort, directional) beams of ions, X-rays and \( \gamma \)-rays

\( \rightarrow \) exploit the unique properties of the ion beam as a probe and for a variety of applications
Two chambers allowing 1 PW and 10 PW experiments and 2-stage schemes

And very long focal lengths up to $\approx 30$ m possible e.g. for electron acceleration
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

$E_{laser}$

electron

positron

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
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 ($I \approx 10^{20} \text{ W/cm}^2$, $a_0 \approx 7$)
  ➢ Comparison to scaling laws and exploratory experiments
  ➢ Injector optimization

• **PHASE 3:** 2019 –
  
  Develop a two stage Laser Plasma Accelerator (injector/accelerator)
  e\textsuperscript{-} beam transport, focusing, synchronisation and injection into a plasma wave over long distance
Ion acceleration
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
State of the art: protons <100 MeV

Today: small fraction of ions are accelerated

Tomorrow: expulsion of all electrons inside the focal spot
acceleration of all ions to high energy
multi-GeV protons at I >10^{23} W/cm^2

1.8×10^{22} W/cm^2, 100 nm, GeV p

T. Esirkepov et al.
Basic studies at \( \approx 10^{22} \text{W/cm}^2 \)

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 system

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

- Neutrons up to several 10 MeV

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

D. Higginson et al., PRL 2015
X-rays, $\gamma$-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
The activities proposed on APOLLON aim at:

- extending the capabilities of the laser-induced radiation sources
  \( h\nu \approx 30 \text{ eV} \) to tens of keV
  energy \( \approx \) a few nJ to a few mJ
  duration \( \approx \) 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
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

UHI100
\[ a_L = 6 \]
Electrons oscillate radially in the bubble during acceleration …

… and emit x-rays

100s keV with PW laser \((\text{GeV } \text{e}^{-})\)

Relativistic flying mirror

Toward short-wavelength compressed and focussed x-ray beams

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

\[ a = 300 \quad I = 1.2 \times 10^{23} \text{ W/cm}^2 \]

Driver

\[ t = 77 \times 2\pi/\omega \]

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

Apollon & Science

[Graph showing fields and intensities]

Apollon 2\textsuperscript{nd} intense beam!

\[ I = 1.2 \times 10^{19} \text{ W/cm}^2 \]
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
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
- Pair production from laser field – Breit-Wheeler

Nonlinear Thomson & Compton scattering

- Generation of high-energy photons

High-energy photons + laser

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Electron – positron pair production

Several mechanisms can produce electron – positron pairs

$E_y$ field and positron & ion profiles

Particle energy distribution

$\approx 10 n_c$ at $10^{24}$ W/cm$^2$
The laser electric fields separate virtual e\(^-\) & e\(^+\) before they annihilate.

Separate the 2 particles by \(\lambda_c\) during their lifetime:

or give each particle an energy \(mc^2\)

\[ E_{Schwinger} = 1.3 \times 10^{18} \text{ V/m} \]

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

\[ eE\lambda_c > 2mc^2 \]

\[ I > 2.3 \times 10^{29} \text{ W/cm}^2 \]
QED effects are “easily” reached!

The electric field in the electron frame can “easily” reach the Schwinger field:

\[ E_{rf} = \gamma E (1 - \beta \cos \theta) \]

\[ E_{rf} \propto \gamma I^{1/2} \quad I \rightarrow I_{rf} = \gamma^2 I \]

With \( I = 2.3 \times 10^{22} \text{ W/cm}^2 \) \( \gamma = 1500 \) [750 MeV] \( \rightarrow E_{rf} = E_{\text{Schwinger}} \)

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