The LUNEX5 project

R. Roux, Laboratoire de l’Accélérateur Linéaire, Orsay, France
S. Bielawski, C. Evain, C. Szwaj, PhLAM/ CERLA, Lille, France
G. Lambert, R. Lehe, A. Lifschitz, V. Malka, A. Rousse, K. Ta Phuoc, C. Thaury, LOA, Palaiseau, France
X. Davoine, CEA-DAM-DIF Arpajon, France
A. Dubois, J. Lüning, LCPMR, Paris-VI, France
G. LeBec, L. Farvacque, ESRF, Grenoble, France
G. Devanz, M. Luong CEA/DSM/IRFU/SACM, B. Carré, CEA/DSM/IRAMIS/SPAM, Saclay, France

Laser à électrons libres Utilisant un accélérateur Nouveau pour Exploitation de rayonnement X de 5ème génération

free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation
I - Introduction: Scientific context

Scientific context and motivation

• Success of XFEL (LCLS, SACLA...) opening for new investigation of matter

• New seeding schemes (HHG seeding, echo, self-seeding) and first seeded FEL for users (FERMI@ ELETTRA, SCSS Test accelerator)

• Progress of alternative accelerator techniques

=> Advanced compact FEL?


T. Togashi et al., Optics Express, 1, 2011, 317-324
Intense laser focussed in a gas jet / cell / capillary => ions : accelerator electric field

**Figure 4**

W. P. Leemans et al., Nature Physics 418, 2006, 696

M. Fuchs et al., 5, 2009, 826

**Figure 5**

L. P. Leemans et al., Nature Physics 418, 2006, 696

M. Fuchs et al., 5, 2009, 826
Laser WakeField Accelerators (LWFA)

1-Introduction : Scientific context


O. Lundh, Nature Physics, 2011

1.5 fs RMS duration : Peak current of 4 kA


Electron beam production

C. Cipiccia et al. Nature Physics, 2011
1-Introduction: Scientific context

Laser WakeField Accelerators

Preliminary experiment LOA/LLR/SOLEIL/CLIO

Progress on the generation of undulator radiation in the UV from plasma based electron beam, G. Lambert et al. THPD47

<table>
<thead>
<tr>
<th>Undulator parameters</th>
<th>Unit</th>
<th>Value</th>
<th>Laser/plasma parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>SmCo</td>
<td></td>
<td>Energy</td>
<td>J</td>
<td>1</td>
</tr>
<tr>
<td>Deflection parameter</td>
<td></td>
<td>1.05</td>
<td>Pulse duration</td>
<td>fs</td>
<td>30</td>
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<tr>
<td>Magnetic gap</td>
<td>mm</td>
<td>3.5-8</td>
<td>Focal length</td>
<td>m</td>
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<tr>
<td>Spatial period</td>
<td>mm</td>
<td>18.2</td>
<td>Aperture</td>
<td>mm</td>
<td>55</td>
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<tr>
<td>Number of periods</td>
<td></td>
<td>34</td>
<td>Target length</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Number of section</td>
<td></td>
<td>1</td>
<td>Electron density</td>
<td>cm⁻³</td>
<td>6*10⁶</td>
</tr>
<tr>
<td>Peak magnetic field at 4 mm</td>
<td>T</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Beyond third generation light source (undulator spontaneous emission, partial transverse coherence), progress towards advanced fourth generation (4G+) light sources (coherent emission, temporal and transverse coherence, femtosecond pulses, high brilliance) via the latest free electron laser seeding schemes and electron photon interaction, to be validated by pilot user experiments,

=> Demonstration of echo at short wavelength
=> FEL physics
=> Advanced design of FEL source for improved performances, associated with cost and size reduction

and towards fifth generation (5G) (Conventional Linac replaced by a LWFA), FEL being viewed as a qualifying LWFA application: evaluation of the LWFA performances in «operation-like» conditions (cf EuRRONAc objectives)

Complementarity CLA / LWFA:
CLA high repetition rate, high reliability, LWFA: ultra-short electron bunch, compacity
II-Project general presentation

LUNEX5 PERFORMANCES

400 MeV, 1.5 π mm.mrad emittance, a peak current of 400 A, a slice energy spread of 0.02% (CLA) and case A : 0.1, case B: 0.5% (LWFA), a bunch duration of 1 ps (CLA) and case A: 2, case B: 20 fs-RMS (LWFA)
PILOT USER EXPERIMENTS

Time and energy resolved studies of isolated species (cold atoms/molecules, clusters, nanopaticles) (C. Miron et al.)

**instrument**: high resolution velocity map imaging spectrometer with full momenta characterisation of electrons and ions using a COLTRIMS type of spectrometer based on time-of-flight and particle 2D position detection (coincidences or “covariance mapping”)

- Electron and nuclear wave packet dynamics in molecules
- Molecular dissociative core-excited states (pump-probe)
- Ultrafast electronic decay processes in weekly bound systems (clusters)
- Auger-Doppler effects and electron tunneling
- Electron streaking measurements to correlate emission delay and structure

Study of magnetisation dynamics (Lüning, LCPMR)

spatially resolved analysis on ultrafast magnetization dynamics following a non-thermal excitation of a ferromagnetic thin film by an intense, fs short IR laser pulse

coherence => single shot X-ray images of the magnetic domain structure

IR pump- X ray probe:

resonant magnetic small angle scattering at the transition metal M-edges

**“pilot user experiments” and not “user’s facility”**

experiments to be developed with the **CLA first**: 20 nm (M 2,3 transition metals), 12 nm (Si)

experiments to be developed with the **LWFA**: higher energies (1.2 GeV?) for the generation of shorter wavelengths (4 nm?) (C (K))

**vision beyond LUNEX5**: LUNEX demonstrator of further facilities enabling:

- the generation of ultra-short pulses (attosecond?)
- access to K levels of C,N,O and L ones of transition metals (< 4 nm)
- “single shot”
- dilute phase – nanoparticules, magnetism, chemical reactivity, biology (time resolved)
**PROJECT PHASES**

**2011 :**
- «Opportunity proposal at SOLEIL»
- SOLEIL discussions with Council members, CNRS (B. Girard, C. Simon)
  DSM (J. P. Duraud);

**June 2011 SOLEIL Council:**
  - CDR request
  - Review by an ad-hoc committee in connection with the SAC
  - Presentation to the dec.
  - SOLEIL Council 2011

**SOLEIL Council preparation Dec-8, 2011**
- CNRS : B. Girard, C. Simon
- CEA - DSM : J. P. Duraud
- SOLEIL : J. Daillant, M. E. Couprie

**RESOLUTION XIII**
The Council takes notice of the LUNEX5 CDR document and approves the start of a targeted complementary studies and associated R&D, on specific funding. He takes note of the coordination role of SOLEIL.

**Targeted complementary studies and associated R&D Phase**
- Start R&D programs and fund search
- Start complementary targeted studies, in particular with respect to the recommendations of the review committee.

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III-Project lay-out and components

**LUNEX5 PROJECT**

**High brilliance Photo-injector**
- typically 1 nC, 1 π mm.mrad, 4 ps rms,
- 100 A peak current
- transverse and longitudinal laser flat-top distribution
- RF gun type: FLASH, EXFEL type

**Compression Chicane**
- Reduction of the bunch length to 1 ps
- Laser heater: enlarges the energy spread
- laser modulation laser in a wiggler to avoid the micro-bunching in the compressor

**Laser heater**

- 200 MeV

**Harmonic cavity (or chicanes)**
- Longitudinal phase space linearisation

**Cryomodule**
- superconducting accelerating section, 24 MV/m, 1.5 ms RF pulse,
- 50 Hz, 10 % duty cycle
- Cryogenic power: 100 W at 2 K

\[ T_f \propto Q_L \]
\[ T_b \]
\[ T_{RF} \]
\[ N_{bunch} \]

5µs-500 µs macropulse
1-100 bunches, 0.1-1 nC, 1-100 µA

jeudi 30 août 2012
III-Project lay-out and components

**LUNEX5 PROJECT**

**Echo modulators**: in-vacuum undulators
- period 30 mm

**Collimation section**: cleaning of the halo and of the dark current
- LWFA chamber
- Echo chicane
  - Chicane 1 (2)
  - Number of dipoles: 4
  - Length: 1.2 (0.8) m
  - Gap: 25 mm
  - Bz: 0.38 (0.35) T
  - L_{d}c: 150 (100) mm

**3 Variable permanent magnet**: transport Qpole: 130 T/m

**Cryomodule**: superconducting accelerating section

**HHG chamber**

**Seed laser**

**CILEX (Centre Interdisciplinaire du Lumière Extrème)**:
- APOLLON laser 10 PW
- LUIRE
- «Proximity centers»: LOA Salle Jaune: 2 beams of 60 TW each, UHI 100, LASERIX...

**Colliding scheme rather than the bubble regime or capillaries**:
- Good beam quality
- Monoenergetic dE/E down to 1 %
- Beam stability
- Tuneable Energy: up to 400 MeV
- Low emittance: \(\pi \cdot \text{mm.mrad}\)
- Adjustable Charge: 1 to tens of pC
- Adjustable Energy spread: 1 to 10 %
- Ultra short e-bunch: 1.5 fs rms
- Low divergence: 4 mrad

**Summary**

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2012, 34th International FEL conference, Nara, Japan, 2012 Aug. 26-31
III-Project lay-out and components

LUNEX5 PROJECT

Multipurpose source chamber for isolated species production under UHV
Full 3D ion momentum spectrometer

Isolated species user station

Condensed matter user station

Monochromator

Beam dump dipole

Quadrupole: 6T/m, 150 mm length, Ø = 25 mm

Echo radiators: in-vacuum cryo-ready undulators period 15 mm

gap 5.5/20 mm
B=1 T

In vac cryo
gap 5.5/18 mm
B=1.15 T

Fig. VII.5 - 1: Scheme of the monochromator proposed for LUNEX5

Multipurpose source chamber for isolated species exp
Full 3D ion momentum spectrometer
CLA electron beam dynamics

«Complete» modeling along the CLA and adaptation to the undulators

Low emittance < 1 \texttimes 10^{-6} \text{ mrad}
Low \frac{dE}{E} < 1 \texttimes 10^{-4}
FWHM pulse duration \sim 0.5 \text{ ps}
400 – 800 A peak
IV- CDR modeling and simulations

**LWFA electron beam dynamics**

Energy : 0.4 - 1 GeV
Few fs : 2 fs = 10 fs
High peak current : 10 kA = 2 kA
Normalised emittance $\gamma \varepsilon = 1 \, \pi \, \text{mm.mrad} = 4 \, \text{mm.mrad}$
Energy spread : between 1% (present value) et 0.1% (targeted value) = 0.2%

Final slice parameters (20 pC)

Decompression with chicane under study

Beam transfer investigations from LWFA to FEL undulator line : see A. Loulergue et al. WEPD05
Towards Compact Short FEL sources : Seeding LWFA based FEL, M. Labat, FROBI01

Simulation LUNEX5 code BETA

**Table**

<table>
<thead>
<tr>
<th>Size</th>
<th>Divergence</th>
<th>Norm. Emittance</th>
<th>Length</th>
<th>E-spread</th>
<th>Q</th>
<th>Peak current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $\mu$m</td>
<td>1.25 mrad</td>
<td>1 $\pi \cdot \text{mm.mrad}$</td>
<td>2 fs</td>
<td>0.1%</td>
<td>20 pc</td>
<td>4 kA</td>
</tr>
</tbody>
</table>

**Compact permanent magnets**

- Spaced by 50 mm
- Normal layout Length 2 m
- Compact layout Length 1.2 m

**PIC-ASTRA/ELEGANT-GENESIS**

CLA and LWFA performances comparison

\[ B_s = \frac{2I}{\epsilon_{sx} \epsilon_{sz} \sigma_{se}} \]

**CLA – 1 nC**

**LWFA 20 pC**

**LWFA**: 1 Hz, 400 MeV and possibly higher.

**Mature and stable, technology mature, solid and fertile base for 4G+ development (HHG, EEHG...)**

**Brilliances rather comparable**

**New promising technology, to be qualified on a laser application such as the FEL**

**Possibly single spike FEL operation**

**Critical parameter: energy spread and beam divergence**
IV-Modeling and simulations

FEL Sources on LUNEX5

Undulator field

CLA : 400 MeV, 0.02% energy spread, 1.5 µm.mrad, 400 A, 1 ps rms

Amplifier @ 20 nm, after 3 sections z = 11 m, 50 MW, 30 fs FWHM, signal/ noise= 3

Cascade @ 20 nm, saturation after 3 sections z = 11 m, 100 MW, 25 fs FWHM, FT

Echo @ 20 nm, saturation after 2 sections z = 7 m, 65 MW, 24 fs FWHM, FT

energy spread : 0.5 %, 20 fs rms; @ 20 nm; so saturation after 3 sections, < MW, > 35 fs FWHM energy spread : 0.1 %, 20 fs rms; @ 20 nm; no saturation after 3 sections, 10 MW, > 20 fs FWHM energy spread : 0.1 %, 2 fs rms; SASE @ 20 nm, saturation after 2 sections z = 7 m, 2 GW, 7 fs FWHM, single spike

LWFA : 400 MeV - 1 GeV, 0.1% energy spread, 1 µm.mrad, 10 k A, 2 fs rms

FEL performances of the French LUNEX5 project : see C. Evain et al.WEPD14

FEL performances at 19.5 nm in the SASE configuration with a LWFA beam.
Electron bunch: $E=400$ MeV, $\sigma_E=0.1/0.5/1\%$, $I=10$ kA, $\sigma_Z=2$ fs-rms. Undulator: 200 periods of 12 mm, $K=1.408$, emittance=1.0 $\pi$ mm.mrad.

FEL performances of the French LUNEX5 project: see C. Evain et al. WEPD14
V- Building and infrastructure

Infrastructure

Greenfield case

SOLEIL booster arena

ALS tunnel

other

VI- R&D actions and targeted studies

Equipments

Variable permanent magnet quadrupole: SOLEIL/ SIGMAPHI/ LOA QUAPeva contract, Triangle de la Physique, C. Benaberrahamane et al., LUNEX5 FEL line magnetic elements: see C. Benabderrahmane et al. THOA04

3 m long cryo-ready undulator
funded in the context of a SOLEIL-MAX IV collaboration, M. E. Couprie/E/ Wallen LUNEX5 FEL line magnetic elements: see C. Benabderrahmane et al. THOA04

Longitudinal laser pulse shaping (PhLAM, CEA-SPAM, LAL, SOLEIL, Faslite ?)
- pulse stacking on a laser at PhLAM : Univ. Lille BQR grant
- spectral components manipulation with a DAZZLER (CEA-SPAM, PhLAM); Enables to easily modify the pulse shape (C. Vicaro et al., Proc. CLEO 2011 (2011) )
- application with a purchased laser on the PHIL electron gun at LAL and validation

Gun
- type PIZT (DESY-Zeuthen, cathode CsTe) /alternatives : C band gun (LAL)
- Tests on PHIL station at LAL with laser shaping

Elementary RF system (SOLEIL, CEA-SACM)
Fabrication of one 9 cell cavity (XFEL type) modified for CW operation; with one solid state amplifier of 15 kW at 1.3 GHz and one LLRF system synchronisation part. Validation with cold tests in CryHolab cryogenic station at CEA, evaluation of the different components in pulsed and CW mode, comparison between 1.8K and 2K

Smith-Purcell Monitor (LAL, SOLEIL...): SP ANR Jeune chercheur, N. Delerue protoptotypes tests at SOLEIL (linac), SPARC, FACET

Cavity BPM: design - tests in the context of CILEX?

Synchronisation: Pulsed fiber laser system to be tested on the femtoslicing project at SOLEIL
Complementary studies

**Electron beam**

- **CLA:**
  - tolerances and full parameter space
  - benchmarking with other codes
  - magnetic compression without harmonic cavity

- **LWFA:**
  - electron beam manipulation / transport matching for realistic LWFA electron beams
  - Calder-Circ (quasi symmetric PIC code simulations of LWFA)
  - s2e simulations
  - 0.1 % energy spread

- **wakefields**

**FEL**

- parameter analysis (laser, upgrades in energy of LWFA)
- LWFA based FEL with relativistic electron beam parameters
- short pulse issues:
  - compression (magnetic chicane, single spike, chirped pulse)
  - bunch manipulation (slotted foil, wavelength selection)
- jitter studies (seeding)
- tolerances
- Triple Modulator Chicane

**FEL radiation transport and monochromator**

Further studies (conservation of the time structure...)

Extension with two FEL lines

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Beam transfer investigations from LWFA to FEL undulator line: see A. Loulergue et al. WEPD05
Towards Compact Short FEL sources: Seeding LWFA based FEL, M. Labat, FROBI01
VI- R&D actions and targeted studies

Test experiments

A «step towards 5G» test experiment under preparation at LOA (SOLEIL, LOA, CEA-DAM):

- up-graded laser : 2 x 60 TW
- new experimental hall
- new electron beam transport starting with relatisitic electron beam parameters (1% energy spread) with a proper handling and matching of the electron beam distribution
- Beam transfer investigations from LWFA to FEL undulator line : see A. Loulergue et al.WEPD05

- new undulators
  - Spare SOLEIL undulators
    * U20, 100 periods, 0.9 T magnetic field @ 5.5 mm gap, in-vacuum type
    * HU60 0.6/0.8 T @15.5 mm gap, 26 periods,APPLE-II
  - R&D 3 m long cryo-ready U15 undulator :
    153 periods, 1.7 T @3mm gap @77k

- Start-to-end PIC to Genesis FEL simulations

Test of seeding with a tunable fibre UV-VUV source

(Erlangen Univ., MAX-Planck, SOLEIL, PhLAM, SPARC, FERMI@ELETTRA, Nova Gorica)

Seeding of SPARC-FEL with a Tuneable Fibre-based source, N. Joly et al,TUPD17

## Conclusion

### Challenges and outcomes of LUNEX5

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success of the echo et seeding innovative schemes at short wavelength (40 - 4 nm)</td>
<td>Component development in close link with industry</td>
</tr>
<tr>
<td>Pilot user experiments (seeding with 1-2 lasers)</td>
<td>Gathering of FEL users around LUNEX5</td>
</tr>
<tr>
<td>Qualification of a LWFA by an FEL application with the different regimes</td>
<td>A step before the collider LWFA application LWFA, contribution to EURONNAc (“Distributed accelerator test facility for synchrotron science and particle physics”)</td>
</tr>
<tr>
<td>Handling of the fs ultrashort pulses for the LWFA and 4G+ based FELs</td>
<td>New applications of ultra-short pulses =&gt; elaboration of a scientific vision beyond LUNEX5 and exploitation of ultra short sources =&gt; new science</td>
</tr>
<tr>
<td>Commun language between laser, LWFA, conventionel accelerator communities</td>
<td>Bridges between scientific domains (multidisciplinary investigations, laser/accelerator synergy)</td>
</tr>
<tr>
<td>Structuration of the activities</td>
<td>Reinforcement of structuration of the local scientific landscape (Saclay area, ESRF, LABEX, EQUIPEX...)</td>
</tr>
<tr>
<td>Scientific excellence and training of future generations</td>
<td>Maintenance and growth of expertise via synergy and mutual exchanges</td>
</tr>
</tbody>
</table>

LUNEX5 is open to new collaborations, in particular for joint R&D or targeted complementary studies.

LUNEX5 project is still very flexible, aiming at advancing on the different R&D subjects.

We continue in the LUNEX5 adventure for ultra short FEL pulses quest, production and use

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Acknowledgments

Many thanks to:

LUNEX5 team

Synchrotron SOLEIL, L’Orme des Merisiers – Saint Aubin – BP48- F-91192 Gif-sur-Yvette CEDEX

General Direction: DAILLANT Jean (General Director of SOLEIL)
Communication Group: GACOIN Marie-Pauline, QUINKAL Isabelle, YAO Stéphaine
Partnerships: CAMINADE Jean-Pierre
Planification, Methods, Quality: ROZELOT Hélène
Security Group: LAURENT Jean-Pierre, PRUVOST Jean-Baptiste

Diagnostics Group: DENARD Jean-Claude, CASSINARI Lodovico, HUBERT Nicolas, LABAT Marie
Magnets and Insertion devices Group: COUPRIE Marie-Emmanuelle, BENABDERRAHMANE Chamseddine, EVAIN Clément, MARTEAU Fabrice, VALLEAU Mathieu
Power Supplies Group: LEBASQUE Pierre, BOUVET François
RF and LINAC Group: MARCHAND Patrick, EL AJJOURI Moussa, LOPEZ Robert, LOUVET Marc, POLLINA Jean- Pierre, RIBEIRO Fernand

Experimental Division: MORIN Paul
Optics Group: LAGARDE Bruno, POLACK François
Instrumentation group: HOLLANDER Philippe
PLEIADES Beamline: MIRON Catalin
METROLOGY Beamline: MERCERE Pascal
AILES Beamline: ROY Pascale
CRISTAL: RAVY Sylvain, LAULHE Claire
TEMPO: SIROTTI Fausto, LÜNING Jan

Technical and development Division: BESSIÈRE Michel
Alignment Group: LESTRADE Alain
Building and infrastructures Group: EYMARD Philippe, FERRARI François
Conception Engineering Group: MARLATS Jean-Louis
Vacuum Group: HERBEAUX Christian

Computing Division: GAGEY Brigitte (Director of the Computing Division)
Acquisition and Control Electronics Group: BETINELLI Pascale, RICAUD Jean-Paul

Administrative Division: LE Ray Yves, Juridics and Procurements: LEROY Michael

Commissariat à l’Énergie Atomique et aux Énergies Alternatives /Saclay 91191 Gif-sur-Yvette CEDEX

CEA, Direction des Sciences de la Matière, SM/ IRAMIS/ Service de Photons Atomes et Molécules: CARRE Bertrand, D’OLIVEIRA Pascal, MONOT Pascal, POISSON Lionel REYNAUD Cécile

CEA, Direction des Sciences de la Matière / IRFU/ Service des Accélérateurs, de la Cryogénie et du Magnétisme: DAËL Antoine, BREDY Philippe, DEVANZ Guillaume, LUONG Michel, NAPOLY Olivier,

CEA, Direction des Sciences du Vivant DSV, LBSR : LE DU Marie-Hélène

Laboratoire de l’Accélérateur Linéaire (LAL), Centre National de la Recherche Scientifique, Université Paris-Sud
VARIOLA Alessandro, BRUNI Christelle, ROUX Raphael

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BIEŁAWSKI Serge, SZWAJ Christophe, EVAIN Clément, LEPARQUIER Marc (Centre d’Études Lasers et Applications)

Laboratoire de Chimie Physique - Matière et Rayonnement (LPCH)- 11 Rue Pierre et Marie Curie, 75231 Paris Cedex 05
DUBOIS Alain, PENENT Francis, LÜNING Jan, PIANCASTELLI Maria Novella, SIMON Marc

Institut des Sciences Moléculaires d’Orsay (ISMO), Université Paris-Sud
DOWEK Danielle

European Synchrotron Radiation Facility
LE BEC Gaël, REVOL Jean-Luc

Fusion for Energy, ITER Department, c/ Josep Pla 2- Torres Diagonal Litoral, Ed. B3, 08019 Barcelona, SPAIN

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