# KAIO Accelerator

## Boosting the broad dissemination of Laser-Plasma Accelerators

Laboratoire d'Optique Appliquée
UMR 7639
INSTITUT POLYTECHNIQUE DE PARIS

***R. Lopez-Martens***

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

***L. Gizzi***

SourceLAB

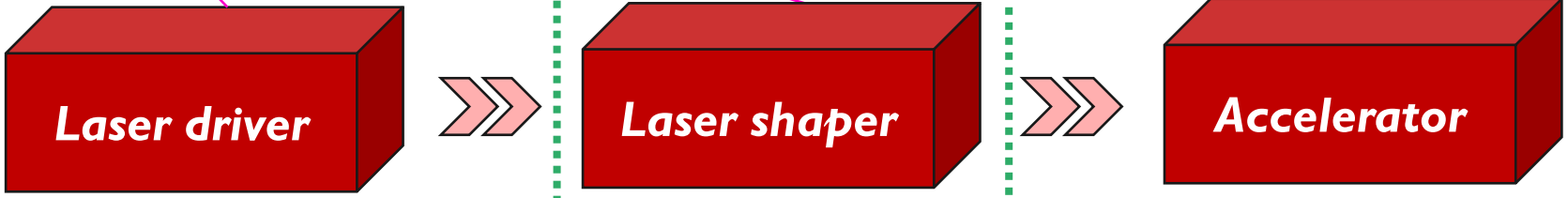
***F. Sylla***

DF Photonics Consulting

***F. Canova***

# Project aim: commercial LPA value chain


***Enabling technologies:***




- ❑ *High average power*
- ❑ *Turn-key*
- ❑ *Cheap & reliable*

- ❑ *Efficient*
- ❑ *Adaptable*
- ❑ *Robust*

- ❑ *Hands-off*
- ❑ *Reliable*
- ❑ *User-friendly*

**Scope of I.FAST-IFF project**

# Project aim: commercial LPA value chain


**Radiobiological testing**

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

**Prototyping**

loa

SourceLAB

**Laser shaper**

- ❑ *Laser pulse shaping for LPA*
- ❑ *Reduce energy required for LPA*
- ❑ *Sustainability via Yb laser technology*

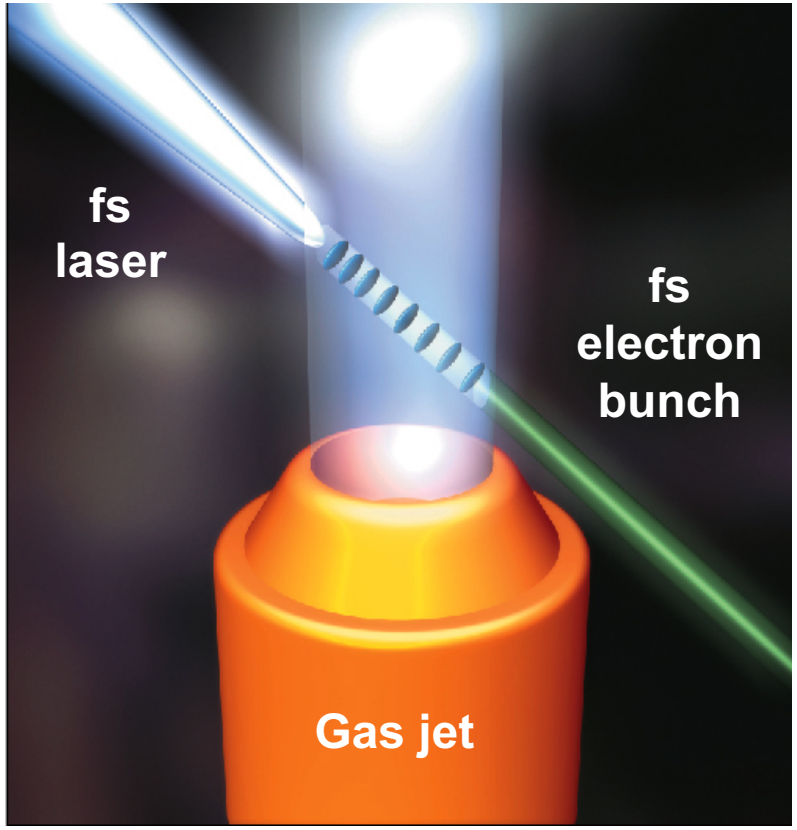
**Scope of I.FAST-IFF project**

**Marketing**

DF Photonics Consulting

SourceLAB

# LPA technology: background




***Laser-wakefield electron acceleration***

Faure et al. Nature 2004
Mangles et al. Nature 2004
Geddes et al., Nature 2004
Lundh et al., Nat. Phys. 2011

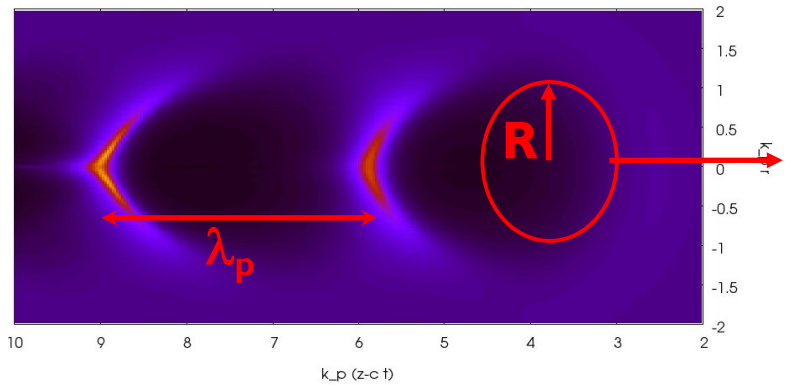
❑ ***Laser driver***
- *Joule-class, 30 fs, rep. rate ~ Hz*
- *Temporal contrast > $10^6$*
- *Intensity > $10^{18}$ W/cm$^2$*

❑ ***Electron properties***
- *0.1 – 10 GeV*
- *Sub-100 $\mu$m source size*
- *Few-fs bunch duration*

❑ ***Electron beams***
- *radiolysis, radiation hardness, radiobiology…*
- *time-resolved electron diffraction*

❑ ***Secondary X-ray beams***
- *time-resolved spectroscopy*
- *radiotherapy*
- *non-destructive probing*

# LPA technology: scaling laws




Laser pulse must be resonant with plasma wave:

$R \approx \lambda_p/2,\ c\tau \approx \lambda_p/2$

**Laser energy scaling:** $E_L \propto \tau^3 \propto \lambda_p^3$ **Electron energy gain:** $\Delta E \propto \tau^2 \propto \lambda_p^2$

**30 fs → 1 J → 100 MeV – 1 GeV**

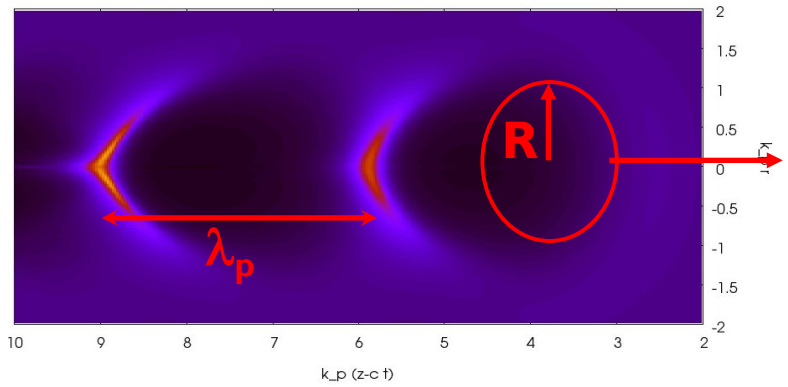
**3 fs → mJ → 1 – 10 MeV** …and high gas jet density ($n_e$>$10^{20}$ cm$^{-3}$)

*Few-fs pulse, few mJ energy → kHz laser technology*
*→ High average power (HAP)*
*→ Enabling for applications*

Lu *et al.*, PRSTAB **10**, 0613001 (2007)

Beaurepaire et al., NJP **16**, 023023 (2014)

# LPA technology: scaling laws




Laser pulse must be resonant with plasma wave:

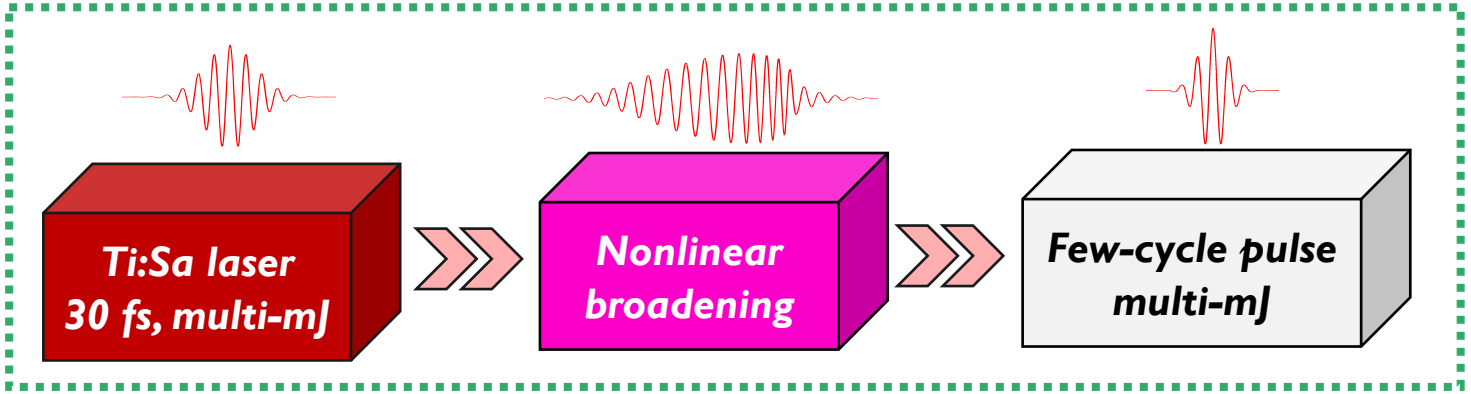
$R \approx \lambda_p/2,\ c\tau \approx \lambda_p/2$

**Laser energy scaling:** $E_L \propto \tau^3 \propto \lambda_p^3$ **Electron energy gain:** $\Delta E \propto \tau^2 \propto \lambda_p^2$

**30 fs → 1 J → 100 MeV – 1 GeV**

**3 fs → mJ → 1 – 10 MeV** …and high gas jet density ($n_e > 10^{20}$ cm$^{-3}$)

***Enabling technology: post-compression***




Böhle et al., Laser Physics Letters, **11**, 9 (2014) , Ouillé et al., Light: Science & Applications, **9**, 47 (2020)

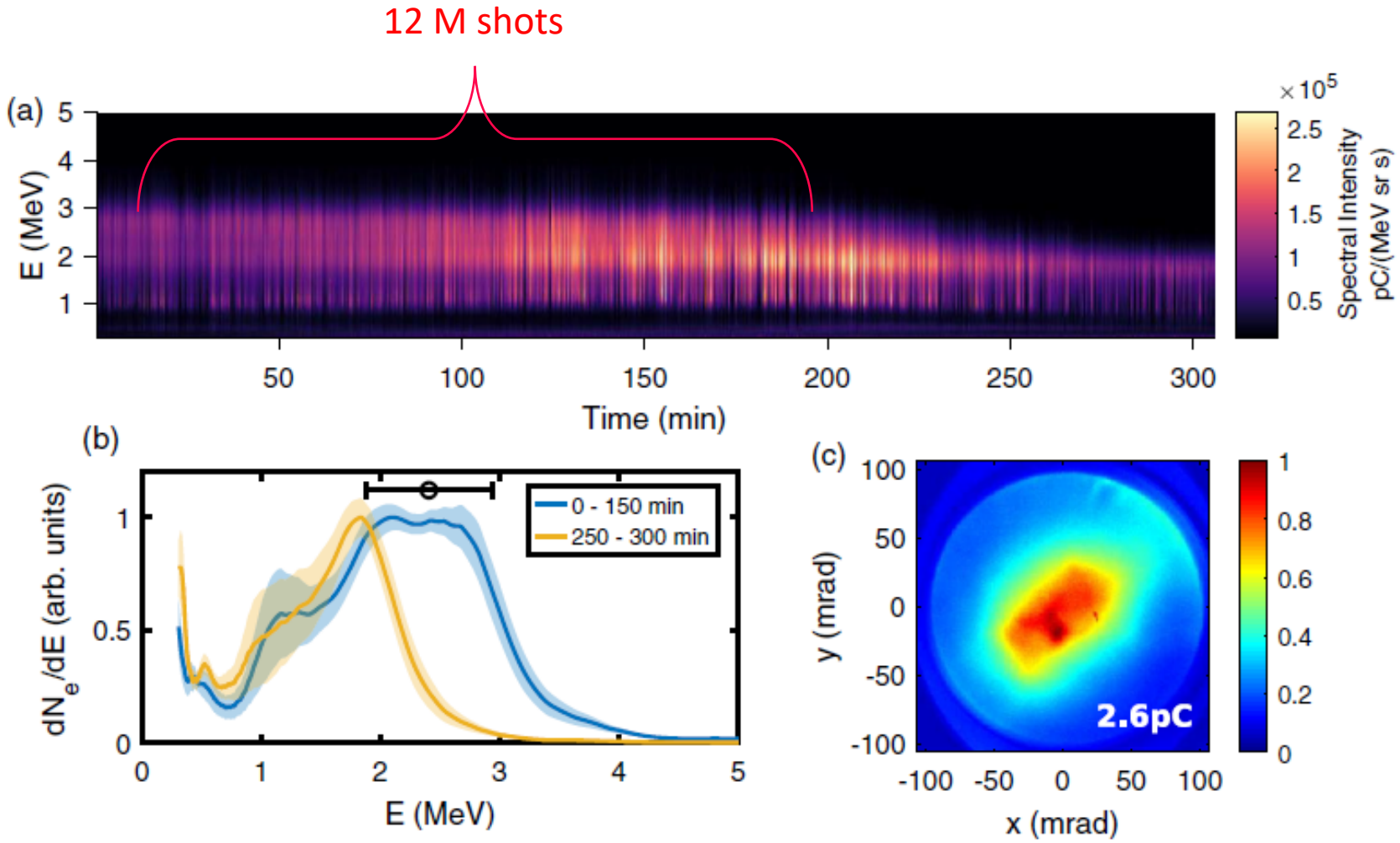
# Long-term LPA operation @ 1 kHz

***Post-compressed Ti:S laser***

- **3 mJ, 4 fs, 1 kHz**
- 3 μm focal spot
- 5 x $10^{18}$ W/cm²
- 200 μm $N_2$ gas jet

***5 hour LPA operation***

***Experiment led by Prof. Jérôme Faure @ LOA***



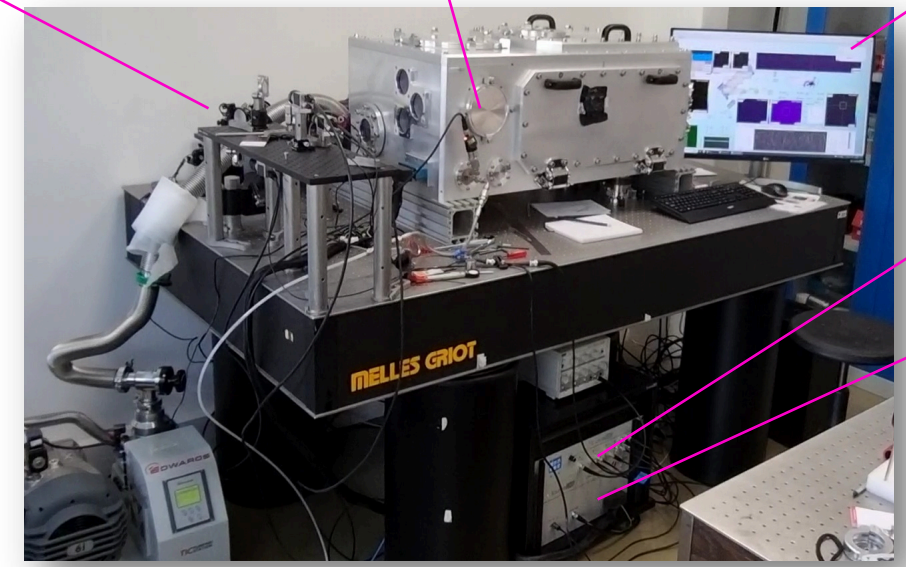

L. Rovige et al., PRAB **23**, 093401 (2020). Similar stability with 200 TW laser: Maier et al, PRX **10**, 031039 (2020)

# LPA technology transferred to SourceLAB

Aluminum vacuum chamber

laser diagnostics

General user interface



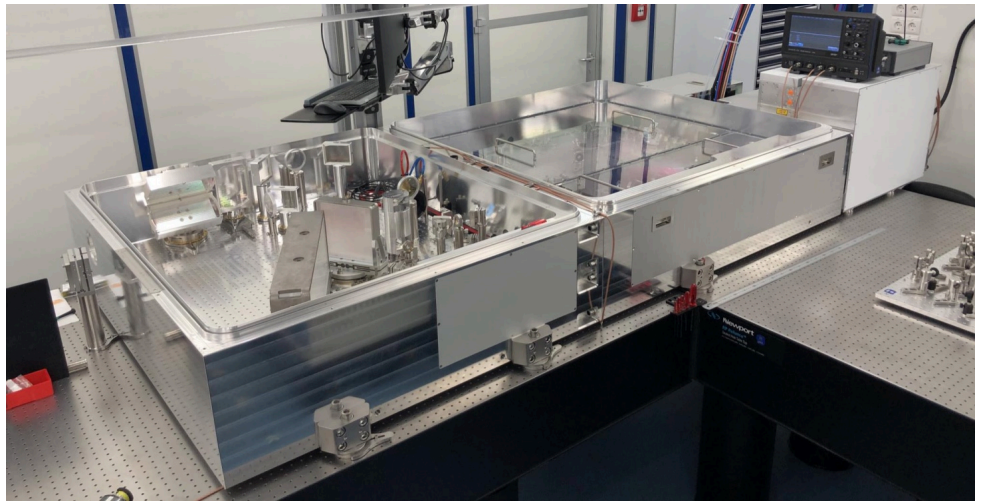

PulseLAB gas jet driver

Motor & CCD controller

**e-KAIO**
**(Kit All-In-One)**
**LPA module**
**(system owner: FZJ)**

- ❑ *Automated alignment*
- ❑ *All-parameter control*
- ❑ *Integrated user interface*
- ❑ *Commercial product*

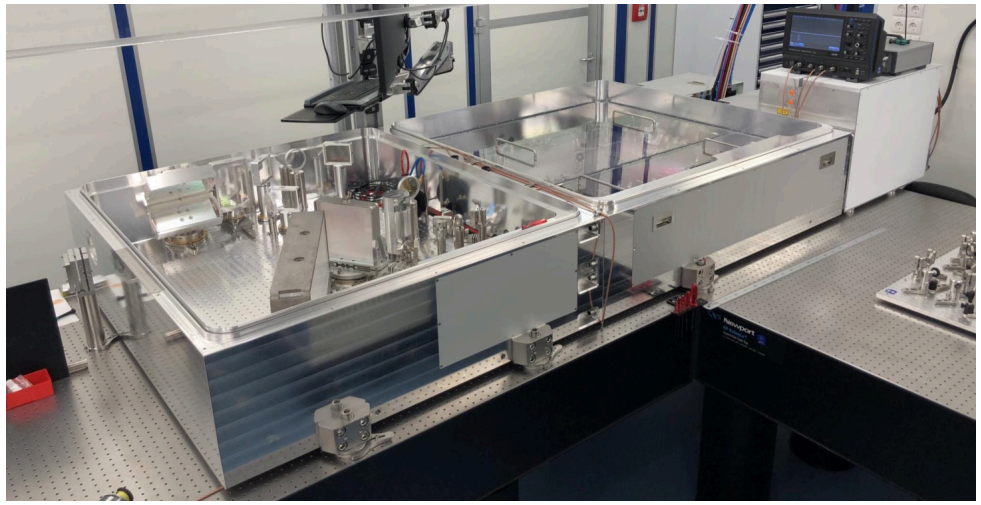
# Emerging Yb disk laser technology



**DIRA 1000-5 from Trumpf Scientific Lasers**
**200 mJ, 500 fs, 5 kHz, 1 kW**

- *0.1 – 1 J, 1-5 kHz, 0.5 – 2 ps*
- *kW average power (Ti:Sa << 100 W)*
- *Industrial grade*
- *Wall-plug efficiency ~ 30 % (Ti:Sa < 0.1 %)*
- *Cost-efficient → sustainability*

# Post-compression with Yb lasers



**DIRA 1000-5 from Trumpf Scientific Lasers**
**200 mJ, 500 fs, 5 kHz, 1 kW**

- *0.1 – 1 J, 1-5 kHz, 0.5 – 2 ps*
- *kW average power*
- *Industrial grade*
- *Wall-plug efficiency ~ 10%*
- *Cost-efficient*

***Nonlinear pulse compression in multi-pass cell (MPC)***

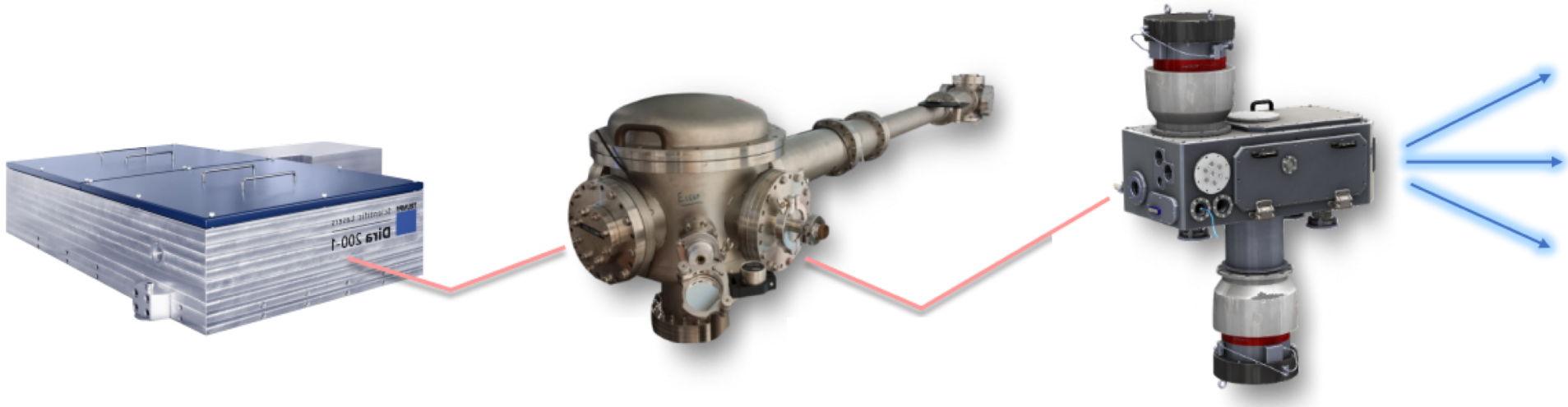
**HERZ module from TSL**


*200 mJ, 500 fs → 180 mJ, 40 fs*

*4.5 TW @ kW average power !*

Pfaff et al., Optica **30**, 10981-10990 (2022).

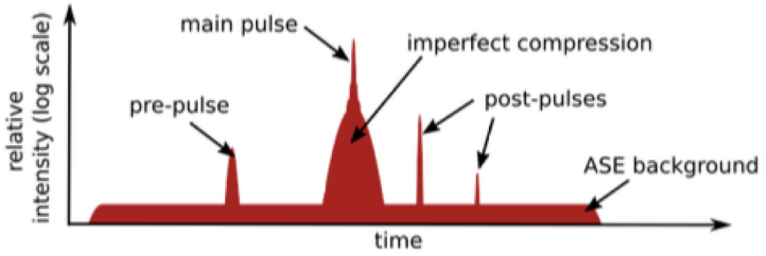
# KAIO-ACCELERATOR: challenges

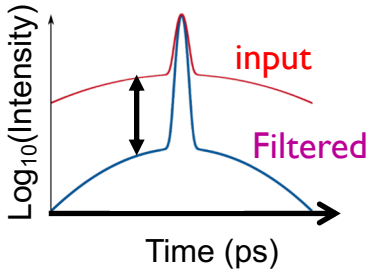


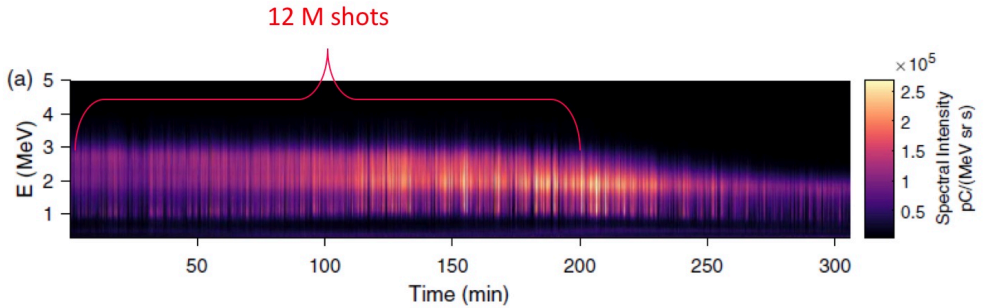
❑ ***Pulse quality ?***
***Constrast < $10^3$***

❑ ***Pulse cleaning ?***
***Contrast $10^3$ → $10^6$***

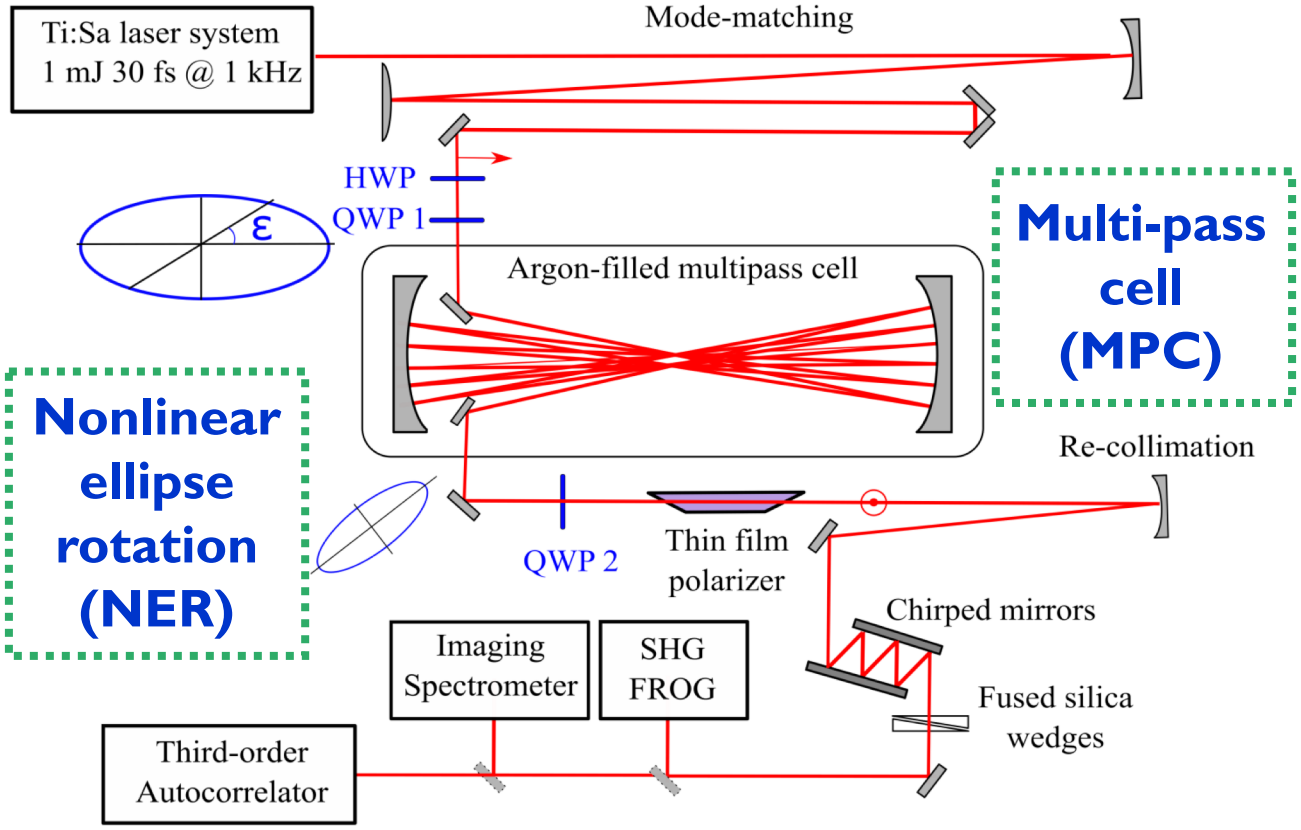
❑ ***Long-term stability ?***
***Stable operation > 5 h***



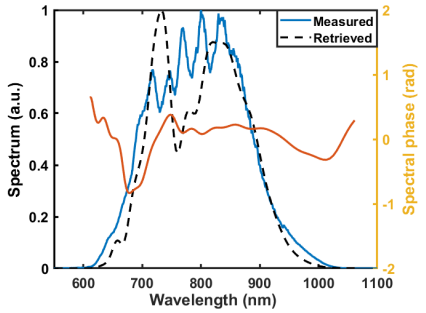



# Pulse cleaning @ LOA

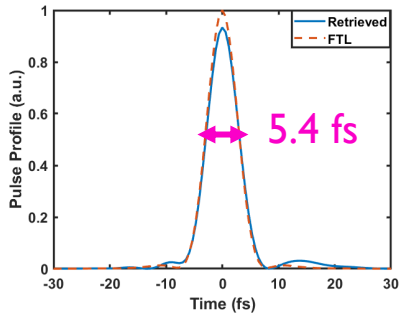



**Newly developed @ LOA:** *Kaur et al., to be published*

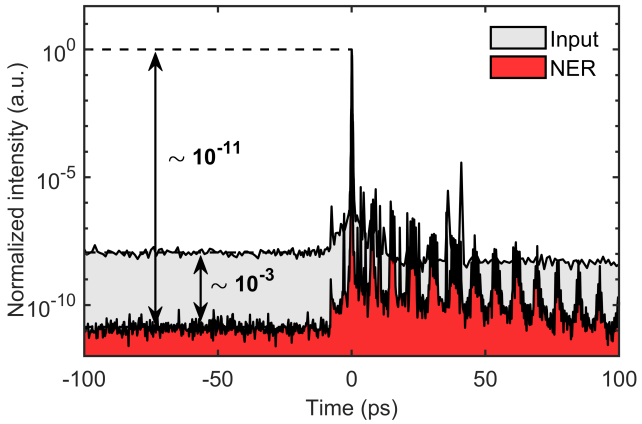
**spectrum**




**pulse**




## Temporal contrast




- *Efficiency > 50 %*
- *Contrast enhancement > $10^3$*
- *Few-cycle pulse regime*
- *Power scalable*

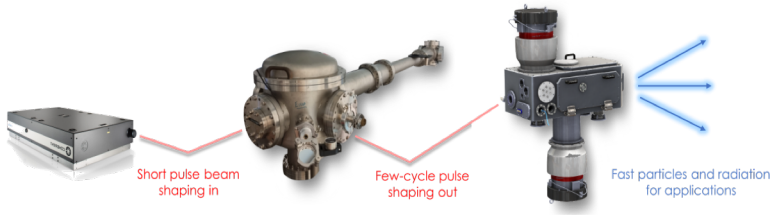
***Review on MPC technology:*** *Viotti et al. Optica 9, 197-215 (2022)*

# KAIO-ACCELERATOR: workplan

Q1 2023

T0 + 6
DL1: report

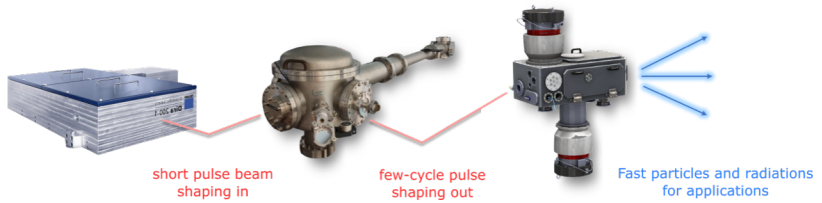
## WP 1
CNRS/LOA
SourceLAB




- ASTRELLA (Coherent)
- 7 mJ, 35 fs, 1 kHz, $10^6$ contrast
- **MPC: 5 mJ, 5 fs, 1 kHz**
- **1st commercial LPA**

T0 + 12
DL1: report

## WP 2
CNRS/LOA
SourceLAB



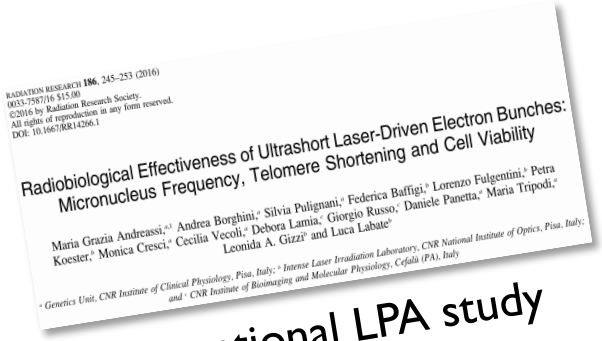

- DIRA & HERZ module (Trumpf)
- 10 mJ, 40 fs, 3 kHz, $10^3$ contrast
- **MPC-NER: 5 mJ, 5 fs, contrast >$10^6$**
- **1st Yb-based commercial LPA**

T0 + 15
DL1: report

## WP 3
CNR/INO
CNRS/LOA
SourceLAB

***Radiobiology tests (DNA single-strand breaking)***

- Dosimetry of e-KAIO electron source
- Dose escalation study with e-KAIO
- **Assess viability vs conventional electron source**


RADIATION RESEARCH 186, 245–253 (2016)
0033-7587/16 $15.00
©2016 by Radiation Research Society.
All rights of reproduction in any form reserved.
DOI: 10.1667/RR14266.1

Radiobiological Effectiveness of Ultrashort Laser-Driven Electron Bunches: Micronucleus Frequency, Telomere Shortening and Cell Viability

Maria Grazia Andreassi,[a,1] Andrea Borghini,[a] Silvia Pulignani,[a] Federica Baffigi,[b] Lorenzo Fulgentini,[b] Petra Koester,[b] Monica Cresci,[c] Cecilia Vecoli,[a] Debora Lamia,[c] Giorgio Russo,[c] Daniele Panetta,[d] Maria Tripodi,[a] Leonida A. Gizzi[b] and Luca Labate[b]

[a] Genetics Unit, CNR Institute of Clinical Physiology, Pisa, Italy; [b] Intense Laser Irradiation Laboratory, CNR National Institute of Optics, Pisa, Italy; and [c] CNR Institute of Bioimaging and Molecular Physiology, Cefalù (PA), Italy

Conventional LPA study

T0 + 24
Final report

## WP 4
DF Consulting
SourceLAB

***Managment, dissemination, exploitation***

Q4 2024

# KAIO ACCELERATOR: ressources and budget

- **CNRS/LOA (Main beneficary):** 2 researchers, 2 engineers, 2 PhD students
- **CNR/INO (Partner beneficiary):** 2 researchers, 1 postdoc, 1 PhD student
- **Sub-contracting:** DF Photonics Consulting
- **SourceLAB SAS:** e-KAIO, ASTRELLA and DIRA laser systems (*in kind*)

| Project | WP1-10W | WP2-100W | WP3-Bio-tests | WP4-Mgt Diss | |
|---|---|---|---|---|---|
| Activity | RTD | RTD | RTD | DEM | Total |
| Man Months | 6 | 6 | 5 | 3 | 20 |
| Labour Cost | 25 800 | 25 800 | 20 200 | 11 600 | 83 400 |
| Travel | 2 000 | 2 000 | 6 000 | 3 000 | 13 000 |
| Equipment | - | - | - | - | - |
| Consumables | - | 42 600 | 5 000 | - | 47 600 |
| Other | - | - | - | - | - |
| Audit | - | - | - | - | - |
| sub total | 2 000 | 44 600 | 11 000 | 3 000 | 60 600 |
| overhead | 6 950 | 17 600 | 7 800 | 3 650 | 36 000 |
| Sub-Contract | - | - | - | 20 000 | 20 000 |
| Budget | 34 750 | 88 000 | 39 000 | 38 250 | 200 000 |
| Funding Requested | **34 750** | **88 000** | **39 000** | **38 250** | **200 000** |

| Partner No | Partner | Country | EC Budget | % Budget |
|---|---|---|---|---|
| 1 | CNRS/LOA | France | **€180 000,00** | €0,90 |
| 2 | CNR/INO | ITALY | **€20 000,00** | €0,10 |
| **Total** | | | **€200 000,00** | €1,00 |

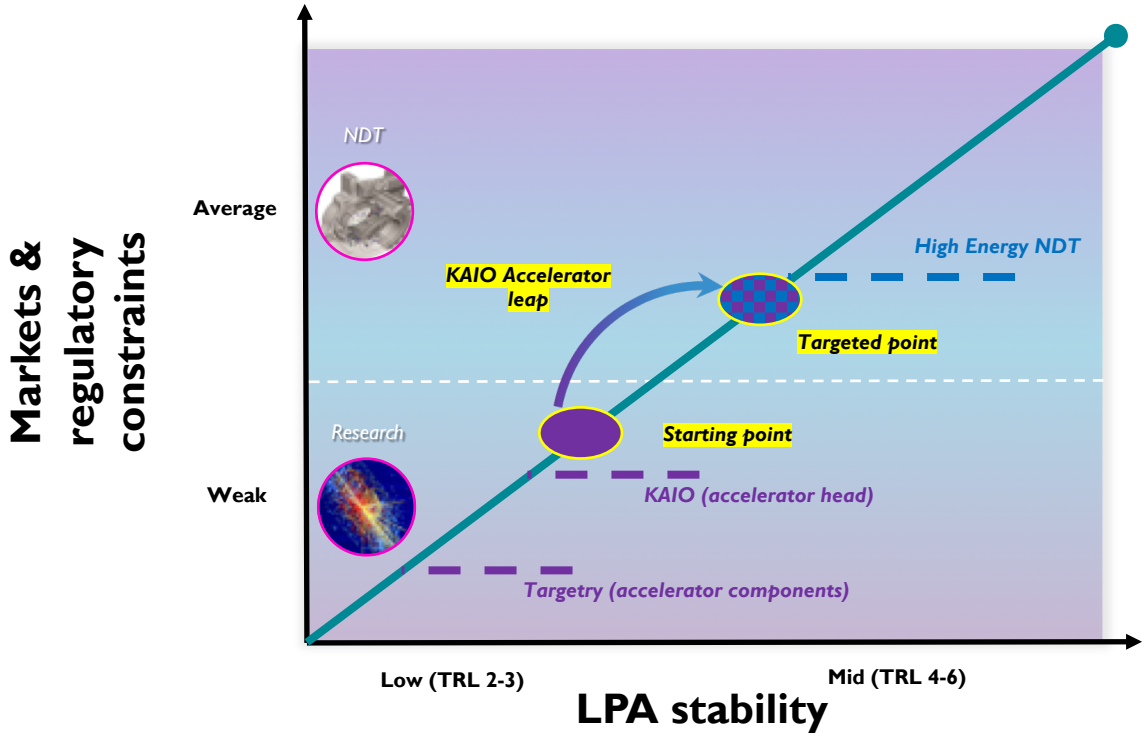
# Performance and risk management

- ***Pulse compression/cleaning with MPC***
  - *Optical damage*
    ***mitigation:*** *different suppliers, cavity upscaling*
    ***risk:*** *less energy for LPA, long-term operation*
  - *Temporal contrast of Yb laser* ***(not reported in the literature !)***
    ***mitigation:*** *cascaded NER pulse cleaning*
    ***risk:*** *less energy for LPA*

- ***LPA testing with eKAIO***
  - *Component failure (nozzles, pumping)*
    ***mitigation:*** *cap laser energy, cap gas load*
    ***risk:*** *long-term operation*
  - *Radioprotection*
    ***mitigation:*** *cap electron energy, local solution, laser shuttering*
    ***risk:*** *long-term operation*

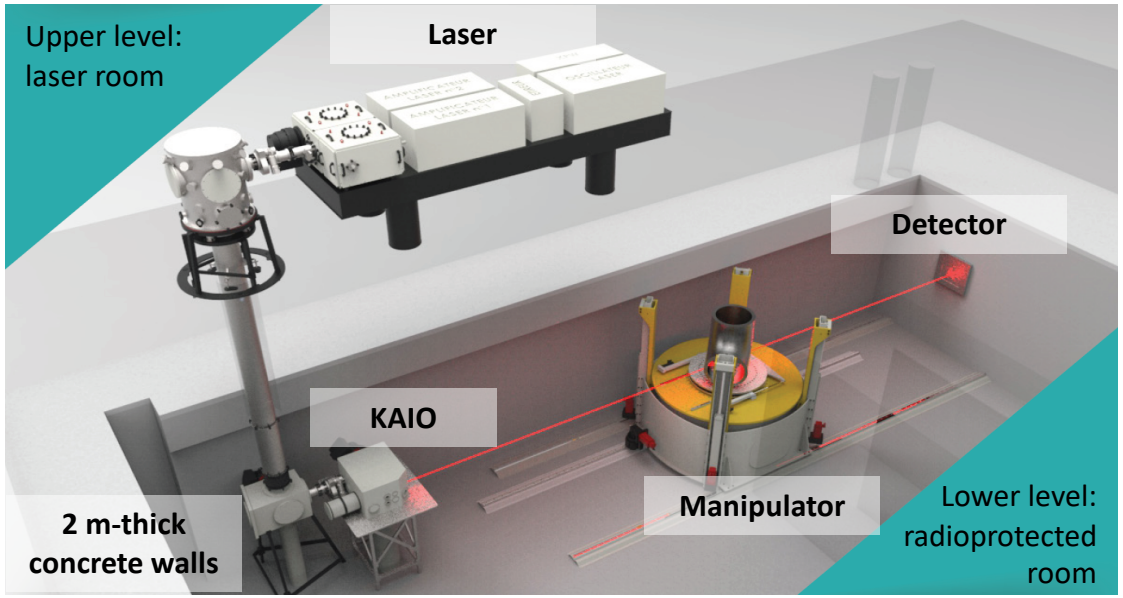
# Background and Business Plan

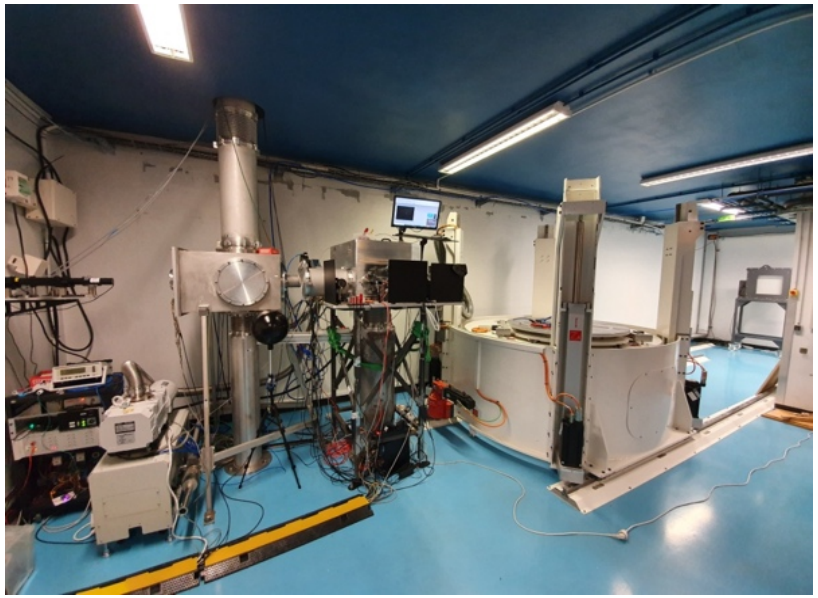
- **Background Academic Partners**:
  - CNRS/LOA is pioneer and world leader in ultrafast laser and laser-plasma interaction science (first demonstration of high repetition rate LPA using laser + post-compression, first demonstration of high-fidelity few-cycle MPC compressor). CNRS/LOA operates state-of-the-art high peak power ultrafast laser and LPA systems.
  - CNR-INO is pioneer and world leader in biological applications of ultrafast LPA beams and operates a 200TW laser facility (ILIL) for LPA development.
- **Background SourceLAB SAS**: company founded after a successful ERC Proof-Of-Concept project (VERTICAL) awarded to Prof. Victor Malka, with the ambition to commercialize LPA-related technology. Thanks to the active collaboration with CNRS/LOA, SourceLAB has integrated the latest innovations in LPA science and now markets the first ever turn-key LPA for applications in science (e.g. FZJ) and industry (e.g. Framatome, DGA).
  - IP: 2 patents owned by SourceLAB and the 2 patents owned by IPP and exclusively licensed to SourceLAB .
  - Awards : BPI France “Creation-Development”, numerous national innovation prizes.
  - Funding : DGA RAPID funding for NDT SHERIL (~€ 1M), Regional funding Feder for NDT SHERIL+ (~ € 0.6M)
  - List of customers and partners : 60+ customers and 10+ partners worldwide (see website)
- **Business Plan**: The initial market estimation is a few ten LPA devices per year and hundreds per year after market customization (see figure below).



# Commercialization of the KAIO Accelerator outcomes

- Once KAIO Accelerator is finalized, the commercialization will be possible thanks to the industrialization of manufacturing site (~1000m² clean rooms) and the partnership with an ultrafast lasers manufacturer
- Then, commercialization by SourceLAB (integrator) through dedicated channels to the industrial customers : a specialized business development team will be created with experts for each industrial sectors (NDT, medical, food industry, space and aerospace, nuclear).
- To prolongate IIF boost funding, we plan the development and customization to the specific need of each industrial sector thanks to EU and national grants and projects. The innovation partners can be co-developers of a version of the technology customized to the specific sector.
- SourceLAB is searching for academic partners to continue to develop the technology, for industrial partners to develop the commercialization in the different sectors and for financial partners to support this ambitious innovation program (~€ 15m estimate for NDT market).
- Thanks to the KAIO Accelerator SourceLab will address a large share of the growing market of laser sources and laser-based applications. The market of accelerator-based machines for industrial and medical applications is estimated in 2022 at 500b$/year. The global high-power, directed laser market should reach $14.6 billion by 2024 up from $8.9 billion in 2019, a compound annual growth rate (CAGR) of 10.3%. The global ultrafast lasers market should reach $8.1 billion by 2022 up from $2.7 billion in 2017 at a compound annual growth rate (CAGR) of 24.7%



Example of an NDT platform implementing KAIO with a low-rep Ti:Sa laser system (SHERIL platform at IPP-CNRS LOA)

# *Thank you for you attention !*

**Contacts:**

**Rodrigo LOPEZ-MARTENS**

rodrigo.lopez-martens@ensta-paris.fr

https://loa.ensta-paris.fr/research/pco-research-group/

**Leonida GIZZI**

leonidaantonio.gizzi@cnr.it

https://www.ino.cnr.it/?page_id=16599&p=a35